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REFERENCE

Lane, B. H., 1935, Suggestions to authors of papers submitted for publication by the United States Geological Survey: U. S. Geol. Survey, Washington, D. C. (For sale by Superintendent of Documents, Washington, D. C. 35c.)

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NOVEMBER 1955

THE GEOLOGY OF THE TEHERAN PLAIN

HUBERT RIEBEN

ABSTRACT. A limited part of the northern Iranian plateau extending twenty miles on either side of Teheran, and lying at the foot of the central and culminating part of the Elburz front range is described.

The only formation in that mountain sector is the Elburz green beds complex, 10,000 feet thick, composed mostly of Paleogene sediments.

Three alluvial formations having their main source in the green beds and resting on the upper Miocene can be distinguished:

A. A lower formation, from 300 to 3000 feet thick, with many aquifers, commonly folded, is designated as Hezardareh and correlated with the Mio-Pliocene or Pliocene "bakhtiari" of the Irano-Iraqian oil field region.

B. An intermediate formation, the Kahrizak, heterogeneous, locally comparable to drift but not glacial, is moderately folded and faulted; its thickness rarely exceeds 200 feet; its age is estimated to be mid-Quaternary.

C. A "Teheran" partially laterized alluvium, affected, in a few places, by orogenic activity, generally less than 100 feet in thickness, represents the subrecent.

The elevation of the Elburz range started in early Pontian (?) time. It was renewed in late Pliocene or early Quaternary. Border thrusts that resulted in a moderate folding and faulting of the Kahrizak over the already folded Hezardareh and finally in overthrusts of the Elburz green beds southward on the upper margin of the plain indicate a very late orogenic phase. The presence of terrace-like levels raises various problems.

The importance of the Hezardareh as a ground-water reservoir is evident. Urgent measures for soil and water conservation should be taken.

INTRODUCTION

Location and accessibility.—The alluvial area described in this paper extends from the center of the city of Teheran for ten miles to the north and twenty miles to the west, south, and east.

From the Karaj river on the west to the Jajerud river on the east the northern limit is the foot of the Elburz Range. The altitude is close to 4500 feet (1350 m) between Karaj and Kan; from here eastward the north edge of the alluviated area rises in a short distance to 6000 feet (1800 m), and it reaches 6500 feet (2000 m) at the crest of the Hezardareh heights near the Jajerud. The city of Teheran occupies a smooth surface with altitudes of 4100 feet (1250 m) on the north, and 3600 feet (1050 m) six miles farther south. The alluvial plain extends southward at least twenty miles beyond the area shown in figure 1 until it reaches, at 2600 feet (800 m), the playas of the salt desert or "kevir." The gently rolling Shemran district just north of Teheran, with Tajrish at its center, contrasts with the mountain slopes that rise from 6000 feet (1800 m) to nearly 13,000 feet (3840 m) within less than five miles.

The alluvial area described here and the foot hills surrounding it are easily reached by car, bus, jeep, or foot, except for some military grounds and a hunting reserve, which are not open to public access.

Physical features and geology.—All rocks cropping out in this section of the front range belong to the "Elburz green beds" (Asfia, Bailey, and Jones, 1948, p. 11), a complex made up of andesite and rhyolite, with tuffs and breccias, black slates, and up to 10,000 feet (over 3000 m) of submarine volcanic mudstones which are thin-bedded, regularly stratified, flint-like, generally light green, and of early Tertiary age.

In the low mountains and hills to the south the alluvial strata rest on upper Miocene salt and gypsiferous sandstones and clays, on purple or brick-red andesitic tuffs or extrusions, and in very limited sectors on Nummulitic limestone.

To the east the "Anti-Elburz" plunges westward near Rey; its hills display mostly Mesozoic calcareous formations, but include sedimentary rocks from Devonian to lower Tertiary, and some volcanic and plutonic rocks.

The designation "Anti-Elburz" is Rivière's (1934, p. 117). It applies to the mountains between the Elburz front and the salt desert, south of a Tertiary basin followed by the highway from Teheran to Semnan via Firuzkuh. The western part of the "Anti-Elburz" is the Sepayeh, a hunting reserve, which ends with a promontory, Mount Bibishaharbanu, in the plain of Rey.

Approximately seven anticlinal ridges, cut by antecedent temporary streams, deform the upper alluvial plain, roughly parallel to the Elburz.

Climate and vegetation.—The Teheran district has a climate warmer than its altitude (4000 feet) and latitude (35° 40′ N) would suggest, since it is protected by its position on a sloping plain at the foot of an east-west culmination of the Elburz Range. From June to September daily temperature maxima range between 86° and 104°F. (30°C. and 40°C.). Winters in contrast are often mild with daily minima between 23° and 40°F. (–5°C. and +5°C.). Exceptional cold spells may keep the ground frozen for several weeks though the temperature rarely drops below 8°F. (–12° or –13°C.).

The ten inches (250 mm) of annual precipitation recorded at Teheran is probably a good average for a zone between the mountainous region to the north and the desert belt to the south. As a rule no rain falls from May to November, though exceptional cloud-bursts occur locally. Snow prevails between 9000 and 13,000 feet (2700 and 3800 m) but usually disappears completely from the southern slopes late in August.

Agriculture and the water problem.—Owing to irrigation, farming is possible on the Teheran plain. Some river water is used but most comes from the "kanat" or "kahriz" system. This system consists of underground waterways leading from shafts which tap ground water in the foothills; it has been supplying most domestic and agricultural water since the system was constructed by the ancient Iranians many centuries ago (Clapp, 1930, p. 77; 1940, pl. 13, fig. 1; Tolman, 1937, p. 12-15).

Primitive dry farming is practiced on moderate slopes between 5000 and 7000 feet (1500 and 2100 m), where wheat and barley may be obtained every other year. Since the slopes have been overgrazed for thousands of years, very few plants except sturdy and thorny cushion-like shrubs and other unpalatable species have survived. These afford some soil protection, but unfortunately even these are disappearing because more and more they are used as cheap

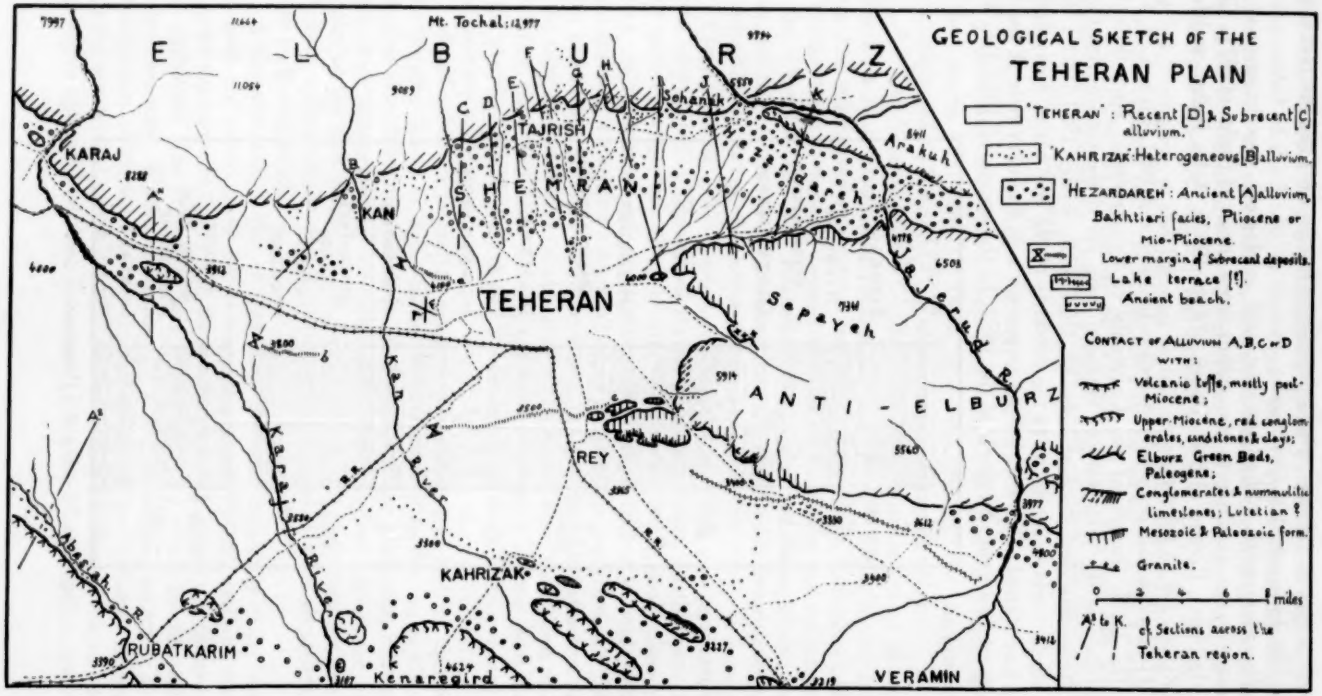


Fig. 1. Geological sketch of the Teheran plain.

fuel by people in Teheran, whose population has grown from 200,000 to over 1,000,000 during the last fifty years.

Previous work.—Physiographic and geological descriptions of the Teheran region available to the author were those of Stahl (1897), Clapp (1930; 1940), Rivière (1934), Bobek (1934; 1937), Asfia, Bailey, and Jones (1948); cf. list of references.

Field work and acknowledgments.—In 1949 and 1951, Prof. C. S. Coon and Dr. L. B. Dupree of the University of Pennsylvania, after their field researches on the prehistory of northern Iran, asked me for information on the Pleistocene deposits near Teheran. During the winter 1951-1952 I therefore made weekly excursions to the outskirts of the city where many excavations had started. This enabled me to present a preliminary note at the University of Lausanne, Switzerland, in 1952. In the spring of 1952 Dr. W. S.

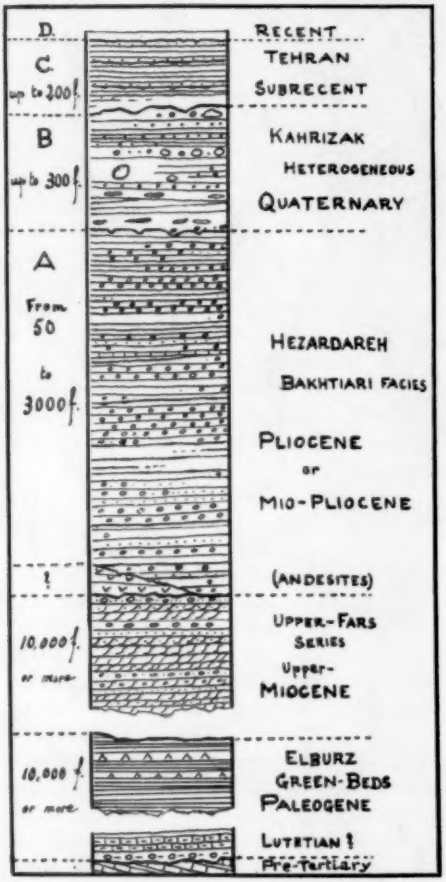


Fig. 2. Columnar section.

Schroeder of the University of Geneva, sent by the Food and Agriculture Organization of the U. N. to investigate the ground water situation in Iran, took interest in my observations. Thanks to him and through the recommendation of H. E. Adl, head of the Seven Years Plan Organization, at the request of the Government of Iran, I was invited by the F.A.O. to study the water-bearing formations of the Teheran region. The present paper gives a résumé of my observations from the fall of 1951 to the spring of 1953. I thank Prof. J. C. Crowell of the University of California at Los Angeles, and Mr. J. T. Gregory, co-editor of the AMERICAN JOURNAL OF SCIENCE, for their invaluable help in reviewing this text.

STRATIGRAPHY

Four stratigraphic units have been differentiated in the alluvial deposits of the Teheran Plain (fig. 2). These, in my preliminary note (Rieben, 1953), were designated A, B, C, and D, in ascending stratigraphic order.

A. The Hezardareh beds.—The oldest and most important of the four units, Unit A, is exposed in ravines crossing the low ridges of the Teheran plain and extensively throughout the higher hills of the Hezardareh district to the northeast of the city, between the foot of the Elburz and the north flank of the "Anti-Elburz." The Hezardareh section of hills west of the Jajerud river, which are crossed by numerous ravines (in Persian *hezar-dareh* means thousand-dales), is here selected as the type locality.

Clapp's article (1930) refers to "Jajerud Gravels," a designation which seems very local for deposits of typical Bakhtiari facies. Furthermore Devonian pebbles which according to him characterize the Jajerud alluvium are found, as mentioned below, together with other Paleozoic and Mesozoic material from the central Elburz, all along the southern margin of the Teheran plain and in several other localities within the ancient folded alluvium farther to the west of Shemran, and also east of the Karaj river (southwest of Kan) as if that river had been flowing out where the much shorter Kan river is at the present time, the late rise of the Elburz front range having caused complex changes in the water courses.

The Hezardareh formation consists of material that had its source, like the overlying B and C units, in the Elburz complex to the north. Close observation shows that the débris is of a small average grain size, ranging between one centimeter and one decimeter. The fragments are more or less angular at the foot of the Elburz, but farther to the south they are rounded, flattened, well-polished, smooth, profusely ornamented with dendrites, and soapy by kaolinization.

A characteristic of this ancient alluvium is the regularity of its bedding. The beds are mostly from five to ten inches thick, though strata of one foot or more are common. Here and there beds of sandy gravel are cemented by lime carbonate. The prevailing hue is pale gray, by which the formation is easily recognized. Within the lower part of the formation, lenticular beds of a terrigenous character become thicker and may predominate. In contrast with the overlying Units B and C, beds exhibiting a reddish color of laterization are exceptional and thin. The result of advanced kaolinization, noticeable

especially in the upper layers, explains the white impervious coat often peculiar to this formation along its outcrops and contacts with overlying deposits.

The Hezardareh in all its outcrops not too distant from the Elburz seems, like the younger units, to be composed of the same material as that which is today washed down from the green beds complex. Dark porphyrites with large phenocrysts and, less frequently, biotite granite, both in advanced stages of disintegration can also be found. To our knowledge these rocks do not crop out in the Shemran Mountains, but much farther to the north or east.

At a distance of a few miles from the mountain foot, up to five percent of the coarse gravel may consist of pebbles of various origins. They represent Devonian quartzites, black Carboniferous limestones, dark-brown Permian limestones, Triassic dolomites, light gray limestones of lower, middle, or upper Jurassic age, lower Cretacic conglomerate, Orbitolina limestone as well as other rocks of possible late Cretaceous age, Nummulitic limestone, or sandy limestone with nummulites. All these rock types are well represented farther north or east in the central Elburz mountains.

One mile and a quarter southeast of Tajrish, in the Qaitariyeh hill, a few boulders of upper Miocene conglomerate were found, the nearest outcrop of which, to our knowledge, is ten miles east, beyond the Hezardareh hills, six hundred feet below their crest (cf. p. 627). The reddish clay observed by Stahl (1897, p. 1) one mile north of Tajrish and much higher, in our zone IV (cf. table 1), was interpreted by him as Miocene but probably belongs to our Unit B or to the base of C.

Close to the Sepayeh east of Teheran the Hezardareh conglomerate contains also impressed pebbles of Lias and other Mesozoic limestones analogous to rocks in formations outcropping in the "Anti-Elburz."

In the Veramin district gravel or conglomerate beds interstratified with typical arenaceous strata of upper Miocene facies have the same aspect and composition as those that constitute most of the Hezardareh formation. This fact suggests that this unit is part of a comprehensive series. The gravel beds are interstratified in the uppermost Miocene, and are precursors to the overlying Hezardareh deposits. These deposits are conspicuous in a high ridge of hills that runs parallel to the southern foot of the "Anti-Elburz," the western part of which appears on the map (fig. 1 and pl. 1-C). This ridge of typical Hezardareh with southwestern dip belongs to a broad anticline deeply eroded into its upper Miocene core by the Jajerud and other antecedent streams. The northern limb, a cuesta-like ridge of Hezardareh conglomerates, is seen several hundred feet higher in the "Anti-Elburz."

Similar relations are seen farther south, at Peshvah, a few miles east of Veramin, a short distance outside the map, and along the northern foot of a ridge, Kuh-i-Ali-Qadr, ten miles west of Karaj and very close to our territory.

Although the Hezardareh formation is concealed under the alluvial sheets of Units B, C, and D, beneath the Teheran Plain, it reappears, constant in its facies, some twenty miles to the south of the city. Here pale green gravel from the unit is noticeable in piles around shafts of "kanats". Farther south it crops out in ridges, and then in cuestas usually facing the south-west. Here more than ten percent of the pebbles come from formations of the Elburz older

than the Paleogene green beds, with Devonian quartzites the most characteristic formation represented. An even higher proportion of these clasts are found in the westernmost outcrops shown on the map (fig. 1), in the vicinity of Karaj. Were it not for their elevation and tilted position they might be confused with Recent alluvium of the Karaj river, in which central Elburz material is also abundant.

In the deposits to the south of the city gypsum is present in needle-like crystals between gravel particles. The gypsum was probably deposited here by groundwater ascending from layers in the upper Miocene which underlies the Hezardareh formation (Stahl, 1897, p. 43).

The Hezardareh beds thin from a maximum of about 3000 feet on the north to less than 100 feet on the south.

An angular unconformity visible in ravines on either side of the Jajerud, up-stream from the highway bridge, separates the Hezardareh into at least two subdivisions. In addition, a low-angle unconformity is evident in the Neyzar ravine three miles north of the Teheran airfield (Mehrabad). Further observations are needed, however, in order to determine whether the upper layers, gently tilted to the north, belong to the Hezardareh or to Unit B. As both units have common lithologic facies, these beds may be strata of the overlying B formation, tilted forty-five degrees southward and resting discordantly on the vertical Hezardareh at the opening of the ravine (fig. 3-C).

B. The Kahrizak formation.—Road cuts and ravines reveal deposits resting unconformably on the Hezardareh gravels and overlain by the stratified alluvium.

Kahrizak, the type locality, is situated twelve miles south of Teheran (Stahl, 1897, p. 43) where the highway to Qum cuts transversely a terrace-like margin of alluvial deposits made of sandy or clayey loam, pale brown loess-like material with patches of gravel, and numerous elongated concretions or nodules analogous to fresh-water limestone.

In the upper zone of the Teheran plain, between the city and the foot of the mountain, the Kahrizak formation commonly begins with a basal conglomerate, up to a few feet in thickness, which is composed of gravel or angular débris. Here and there caps of these gravels have protected the less consolidated Hezardareh beneath from erosion. In fact only this conglomerate may represent the Kahrizak formation here. Stratified gravels may at places alternate with or pass laterally into lenticular beds or masses of the terrigenous or loess-like material predominant at the type locality. On the road to Tajrish thick layers of terrigenous clay have fissures filled with crystallized gypsum and enclose boulders up to three or four feet in diameter. In the same area, within or close to the upper or lower portion of these deposits, there are long successions or aggregates of boulders and blocks, which differ considerably in their dimensions. All these blocks represent types in the Elburz green beds complex; the massive volcanic rocks and breccias are most common (p. 637).

Although where regularly bedded these deposits can be easily mistaken for the Hezardareh, they can nevertheless be differentiated by the presence of irregular splotches which have been stained yellow, yellow-brown, or black by

iron or manganese oxides. This staining affects particularly layers of loose pebbles or unconsolidated sandy gravel where ground water has had easy access.

Local accumulations of reddish clay-like material are found in places at the base of this heterogeneous formation and even more commonly at its top. This material may contain white specks due to particles detached from the kaolinized surface of the underlying Hezardareh. What might here be taken as a top layer of the formation B, however, may prove to belong actually to the overlying subrecent, as indicated below.

In thickness, the Kahrizak is extremely variable. At one extreme it may be reduced to a mere layer of scattered boulders not distinguishable from those of the subrecent C. Sections from ten to thirty feet thick, and even up to fifty feet, can be seen in road cuts or along ravines. In deep ravines, which dissect ancient alluvial fans, up to 200 or 300 feet of these deposits are exposed. Information obtained from "kanat" diggers and the material gathered around shafts indicate that both the Kahrizak and overlying subrecent alluvium thicken considerably along the northern side of the ridges that wrinkle the alluvial plain. Below the city, near Rey, just north of the Mesozoic anticlines that plunge westward from the "Anti-Elburz," the only well logs obtained in the region indicate a thickness of approximately 250 feet (74 m).

The heterogeneity of the Kahrizak formation, in particular between Teheran and the foot of the Elburz has suggested to Rivière (1934, p. 75-76), and lately to other geologists the presence of moraines. To my knowledge however no true evidence of glaciation has been found on the southern slopes of the Shemran mountains and the possibility of the existence of glaciers there seems to have been disproved by Bobek (1937, p. 164).

C. The Teheran alluvium.—The even surface of the alluvial plain is generally underlain by the Unit C, the Teheran alluvium, which is distinguished by its red conglomerate crusts of laterite. In the northern section of the city, wherever shallow excavations have been made, the uppermost red crust is revealed a few feet below the surface. Between Teheran and the foot of the Elburz its coarse but regular stratification is uniform with a dip increasing from one to five percent in a distance of about eight miles. Its northward extensions form the top of ancient alluvial fans, and finally it lies against some of the moderate slopes of the Elburz and is visible even on remnants of terrace-like platforms up to 8200 feet (2500 m) (Stahl, 1897, p. 1).

In the northern parts of the city three to four similar conglomeratic crusts are met at increasing depths about ten feet apart, each from one to three feet thick. Between are layers of coarse sand, gravel, cobbles, and rare boulders. In fact the whole presents the same aspect as the superficial recent outwash, Unit D. From place to place the reddish material, even that beneath the deepest crust, thickens to fill small ravines on former eroded surfaces. During prolonged interruptions in the deposition, the pebbles had time to become coated with calcareous tufa, formed in the same way as today under present climatic conditions.

The thickness of the subrecent Teheran deposits, where trenches have been dug near the margin of the brownish-red areas that characterize their

presence, is from one foot to thirty feet. In a few deep ravines, sections from 50 to 150 feet may be observed, but as no log records are available only a rough estimate can be made regarding the maximum thickness. It may however reach 300 feet.

The lowest part of the Teheran formation is commonly a red, terrigenous sheet of small, decomposed débris, poorly stratified and exceeding three to four feet in average thickness, increasing southward. In and beyond the southern suburbs this homogeneous material alone represents the subrecent formation. It has been extensively used as brick clay. Near its southernmost margin it is eroded into typical bad lands (table 1, X-c), where the surface of the ground drops twenty to thirty feet to the level of the irrigated plain of ancient Rey, the subsoil of which is fifteen feet deep and very rich in archeological material.

D. The Recent.—The shallow veneer of gravel on which most of the city of Teheran is built differs but slightly from present day outwash in alluvial fans. All its material, like that of the subrecent, is made from débris washed southward from the Elburz front range, the Shemran mountains, whose summit, Mount Tochal, 12,977 feet high (3840 m), towers 9000 feet above the city and only twelve miles to the north.

AGE AND CORRELATION

Observations on the "Fars series," intensively studied lately by oil geologists working in the Qum district one hundred miles south of Teheran, have not as yet been published. In our attempts at correlation information gleaned from two remote but equally distant and opposite regions, the Iran-Iraq oil fields to the southwest and Azerbeijan to the northwest are at our disposal. It is of interest to note that in both regions, thanks to the presence of *Hipparion* remains (Lees, 1938, p. 145; Rieben, 1935, p. 42), beds transitional from the "Fars" to the "Bakhtiari" series are referred to the Pontian or Mio-Pliocene.

In the Teheran region the only fossils I found were a few broken fresh water shells in a handful of clay recorded from a depth of 375 feet (115 m) below the surface, from a deep well north of Rey. The blue clay with its faunule suggests correlation with fresh water shales interstratified with yellow shales and lignite, which crop out east of Tabriz in Azerbeijan and are attributed to the Pontian. There the beds rest conformably and gradationally upon clays and limestones which pass down into red conglomerates and sandstones, typical of the upper Miocene. The Teheran faunule, on the other hand, because of the small size of the shells and the relatively shallow depth where they were found, probably correlates with beds stratigraphically higher than the lignite and transitional layers mentioned above. Perhaps it correlates with beds containing fresh water mollusks and small fish, *Brachylebias persicus* Priem and *Leuciscus sp.*, attributed to the Pliocene southwest of Tabriz (Rieben, 1935, p. 49).

Schroeder, who was familiar with formations in southwestern Iran, had the impression that the ancient alluvium crossed by the Qum-Teheran road, 16 miles south of Teheran, corresponds to the Bakhtiari conglomerates. Ac-

cording to the geologists of the former Anglo-Iranian Oil Co., the "Bakhtiari series" is of Mio-Pliocene age (Lees, 1938, p. 144-145), and rests on the thick "Fars series" of the upper Miocene. In facies the upper Fars is similar to the red conglomerates, sandstones, and clays which underlie our Hezardareh. According to my previous observations in Azerbeijan (Rieben, 1935, p. 27), it represents the "formation gypso-salifère" attributed to the Tortonian and Sarmatian.

As for the main part of the Kahrizak formation lying in angular unconformity on the Hezardareh, only fragments of a rhinocerid's jaw have been recovered (Rivière, 1934, p. 68). According to the description available to Rivière who provisionally assumed that the species in question is of Pontian age, it came from the subhorizontal beds designated as Kahrizak in the present paper (cf. p. 623 and p. 630). His statement that "the substratum of these beds is not known in the Teheran plain" shows that he, like other geologists (except Stahl), had not had the opportunity to see the highly tilted and vertical beds of the Hezardareh in the ravines to the east and west of the locality mentioned; or that, unaware of their dip, which indeed is not always clearly visible, he had considered them as parts of the same formation to which belong the subhorizontal deposits he describes and which undoubtedly are our Kahrizak. Since I undertook my researches, extensive excavations have taken place, and the angular unconformity between the two formations is clearly exposed near the western Shemran road. Moreover it still remains doubtful whether the bones came from the subhorizontal Kahrizak as Rivière's text indicates, or from the underlying Hezardareh present at a very shallow depth. I am inclined to think that they came from the Hezardareh.

It is only fair to take into consideration here Stahl's observation in his little known but important paper (1897, p. 1) " . . . in the Shemran mountain region, hills are constituted mainly of outwash, gravels and loose conglomerates. However the core of these hills is made of southward-dipping gray salt-containing Miocene clays which are seen in some deeply eroded ravines." These are indicated as Neogene on his map (1897, pl. 1) and cross sections (1897, pl. 4). I have no doubt that this Miocene and Neogene correspond to our Hezardareh and Kahrizak formations.

Regarding the "Teheran" laterized alluvium, to our knowledge only upper Paleolithic (Mousterian?) artifacts help in dating it. Two paleolithic instruments were found to the northwest of Teheran in 1939 and 1949. The calcareous crust still adhering to them suggests that they were most probably detached from Teheran beds. In this reddened alluvium it is easy to find green cherts or flint-like fragments that very doubtfully were used by prehistoric men.

STRUCTURE

Older folding.—As stated previously the Teheran plain is wrinkled by lines of low ridges that run nearly parallel to the Elburz. Seven of these features varying from one mile or less to six miles in length can be detected (Rieben, 1953, p. 4).

All are anticlinal or monoclinal hills striking west-northwest, or northwest where they are found east of the city. There are exceptions to this trend

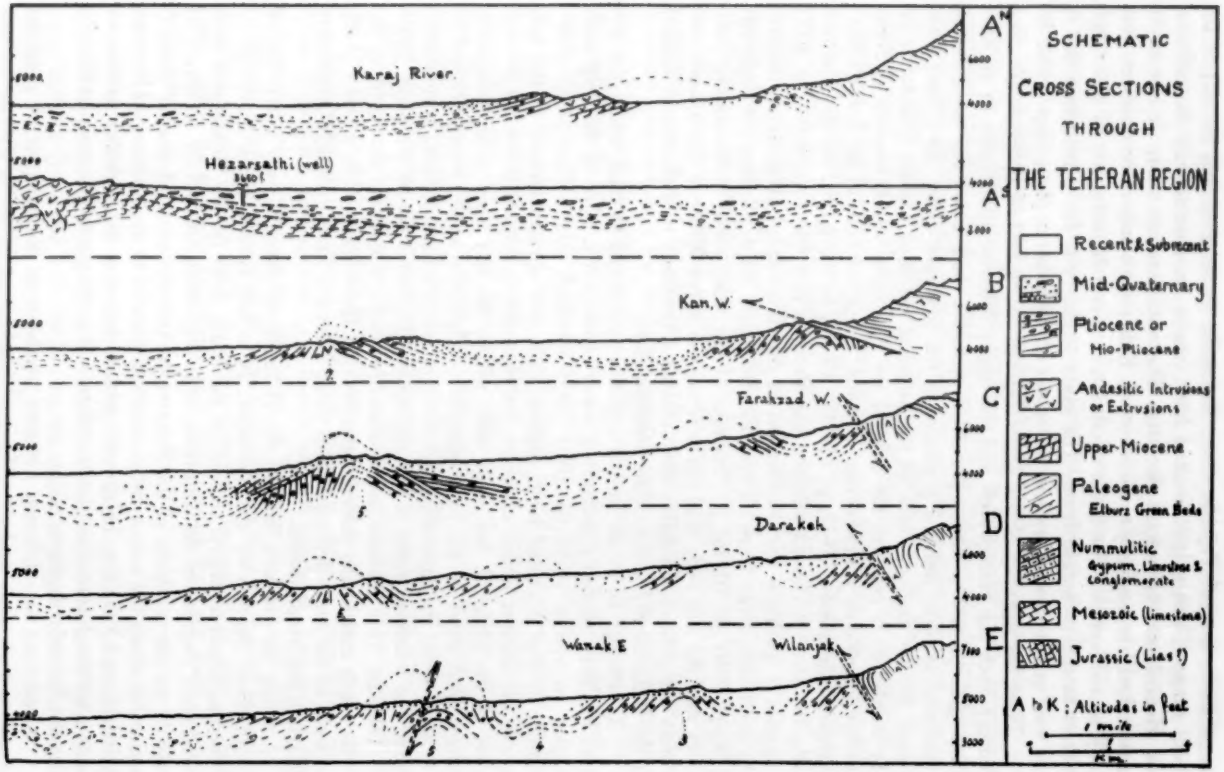
as at Ewin west of Tajrish where the strike is more or less normal to the front range. These ridges resulted from intense tectonic activity that affected the Hezardareh throughout the area. The anticlines are more or less asymmetrical with a tendency to be reversed. Either the southern or northern limb may be subvertical. The latter condition is more characteristic of the ridges closest to the mountain front. The main tendency is for a moderate dip to the west and southwest towards the center of the Teheran plain (figs. 3 and 4).

Near the opening of the upper Jajerud valley east of Sohanak (or Shuhanak) both the Hezardareh and the upper Miocene participate in an anticline (cf. p. 633), whose periclinal outcrops and axial dip towards the northwest seem to indicate a plunge of the structure under the Elburz front range. In the east, the core of the anticline contains Liassic limestone; on the northeast, it contains the base of the Paleogene which consists of Nummulitic limestones, conglomerate, gypsum, and green beds of the lower Elburz complex (Schroeder, 1945, p. 31-33). All dip to the north. On the southern side, the zone of contact between the Miocene and the Hezardareh (p. 622) suggests a tendency for décollement of the thin-bedded Hezardareh towards the southwest, away from the consolidated, more rigid, Miocene conglomerate (Clapp, 1940, pl. 10, fig. 3). Seepage of salt water close to the contact indicates that the salt beds that characterize the upper Miocene throughout west Persia are present. Probably they created a tendency to disharmonic folding in the Hezardareh blanket of the Teheran plain.

An attempt to locate buried anticlines presumed to exist under the city area has been made by measuring water conductivity. Most of the deep wells drilled in recent years (p. 638) yield relatively high mineralized water, similar to that obtained from shallow wells and springs located in the hills where the ancient folded alluvium, the Hezardareh, stands above the average level of the plain. A few deep wells within the city area yield moderately mineralized water of the same electric conductivity as the water drained by "kanats" from the superficial subrecent or intermediate deposits accumulated along the northern sides of the anticlinal hills found across the plain, north of Teheran. This contrast in conductivity seems to indicate that most of the wells reach anticlinally folded water-bearing Hezardareh while a small group of wells of the same depth produce water from synclines in which Quaternary alluvium has accumulated.

Along its southern margin the Hezardareh shows a very gentle dip of about three degrees to the northeast. In a hill twenty miles southwest of Teheran, however, lateral erosion by the Karaj river reveals Hezardareh beds tilted sixty degrees to the southwest as if they were affected by a renewal of activity on the outskirts of the Kenaregird volcanic mass. A similar trend is noticeable along the minor ridges that run parallel to the Kenaregird between Kahrizak and Veramin. In general, within that area the andesitic extrusions have tilted the Nummulitic limestones as well as the upper Miocene, and finally also the Hezardareh deposits.

Conditions are different however northeast of Rubatkarim. A road cut exposes a red, most probably Miocene conglomerate dipping sixty to seventy degrees southwest, while nearby the blanket of ancient alluvium remains al-


Karaj River
Hezarsalhi (well)
Kan, W.
Farahzad, W.
Darakeh
Wanak, E
Wilanjak
A
B
C
D
E
SCHEMATIC
CROSS SECTIONS
THROUGH
THE TEHERAN REGION
Recent & Subrecent
Mid-Quaternary
Pliocene or
Mio-Pliocene
Andesitic Intrusions
or Extrusions
Upper-Miocene
Paleogene
Elburz Green Beds
Nummulitic
Gypsum, Limestone &
conglomerate
Mesozoic (limestone)
Jurassic (Lias!)
A to K : Altitudes in feet
1 mile

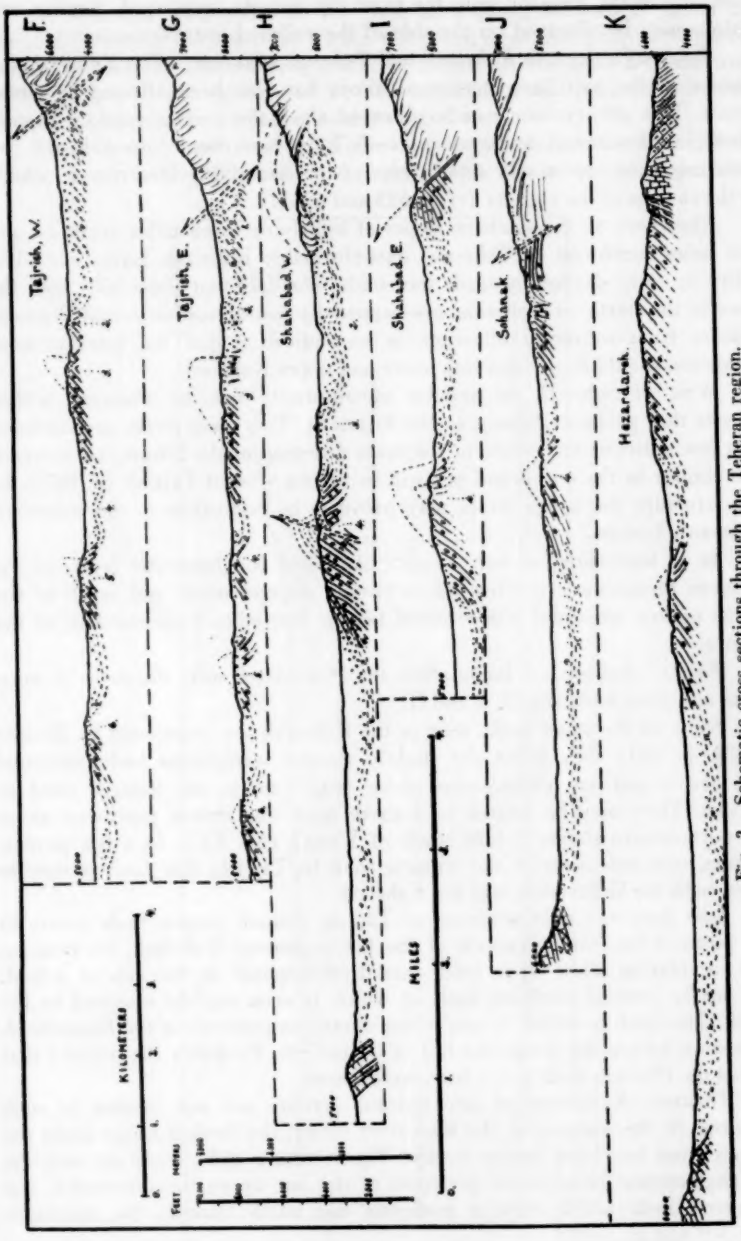


Fig. 3. Schematic cross sections through the Teheran region.

most horizontal, showing only the faint dip already mentioned. Similar conditions may be observed on the side of the railroad near Veramin.

Folds affecting the Kahrizak and Teheran alluvium.—The Kahrizak formation in the anticlines mentioned above has also been affected by lateral forces. This phenomenon can be observed along the western road to Tajrish. There, subhorizontal terrigeneous beds have been bent into a broad low anticline; they cap steeply tilted strata of the underlying Hezardareh, visible in the ravines of the vicinity (cf. p. 623 and 626).

Elsewhere on the southern slopes of hills lying seven miles northeast and five miles northwest of Teheran, unconformable Kahrizak layers are tilted thirty to sixty degrees towards the south. The fact that these hills, like the ones to the north of Teheran, are capped by coarse subhorizontal deposits, distinct from subrecent alluvium, is an indication that the heterogeneous formation should be divided into lower and upper Kahrizak.

West of Sohanak an angular unconformity can be observed within gravels that probably belong to the Kahrizak. The lower strata are included in a low anticline transverse to the main direction of the Elburz, an aberrant one similar to the one found at Ewin two miles west of Tajrish (p. 627). In this structure the upper strata may prove to be equivalent to the subrecent Teheran alluvium.

In at least three or four localities laterized conglomeratic layers of the Teheran formation are tilted ten to twenty degrees north and south of the flanks of low anticlinal hills situated two to five miles from the foot of the Elburz.

Faults.—Subvertical faults affect the Hezardareh near the cores of some of its anticlinal folds (fig. 3, E and H).

Some of the small faults seen in the Kahrizak are mentioned by Rivière (1934, p. 68); they affect the slightly warped terrigenous bed mentioned just above and are conspicuous along road cuts in the western road to Tajrish. They may be related to a strike fault that strikes northwest along the northeastern slopes of hills south of Wanak (fig. 3-E). In a few narrow ravines, one mile west of the western road to Tajrish, this fault is seen to affect both the Hezardareh and the Kahrizak.

Less than one mile southeast of Tajrish a small reverse fault occurs in the moraine-like sandy gravels of the heterogeneous Kahrizak. Its position and orientation allow us to infer that it corresponds to the axis of a fold, the nearly vertical northern limb of which is even slightly reversed to the north. This limb is visible in one of the numerous outcrops of the Hezardareh formation within the dome-like hill of Qaitariyeh. Evidently the activity that folded the Pliocene beds had a later revival here.

Thrusts.—Evidences of late tectonic activity are not limited to such features. At the opening of the Kan river valley, the foothill bulge along the Elburz front has been deeply eroded. The resulting cliff reveals an anticline of fanglomerate Hezardareh protected at the top by an unconformable cap of green beds which have a moderate dip north towards the mountain (fig. 3-B and pl. 1-D).

At Wilanjak, two miles to the west of Tajrish, subvertical faults are revealed in recent garden cuts. Within the green beds that have been moved southward onto the Hezardareh, a slice of folded detritus with a Hezardareh aspect is unconformably covered by red material of Kahrizak or subrecent age and is now squeezed within a miniature graben.

Ten miles north-northeast of Teheran (west of the sanatorium of Shahabad), low outliers of the Elburz project from the mountain slopes, and

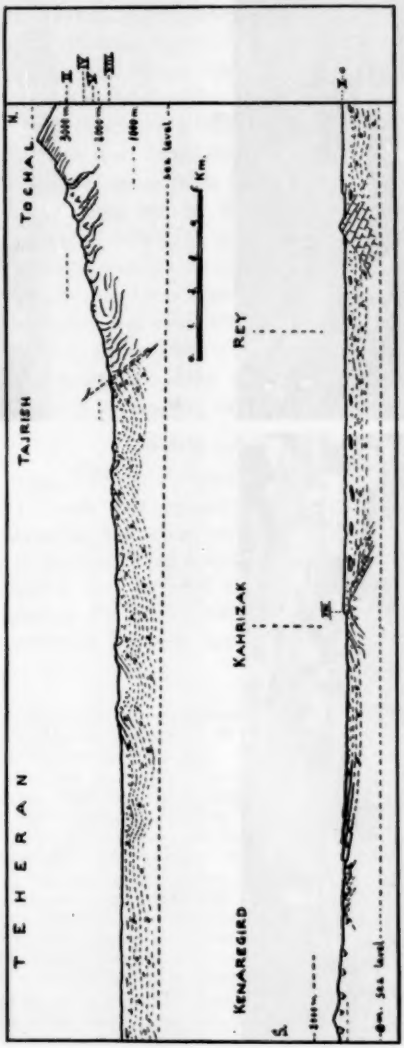
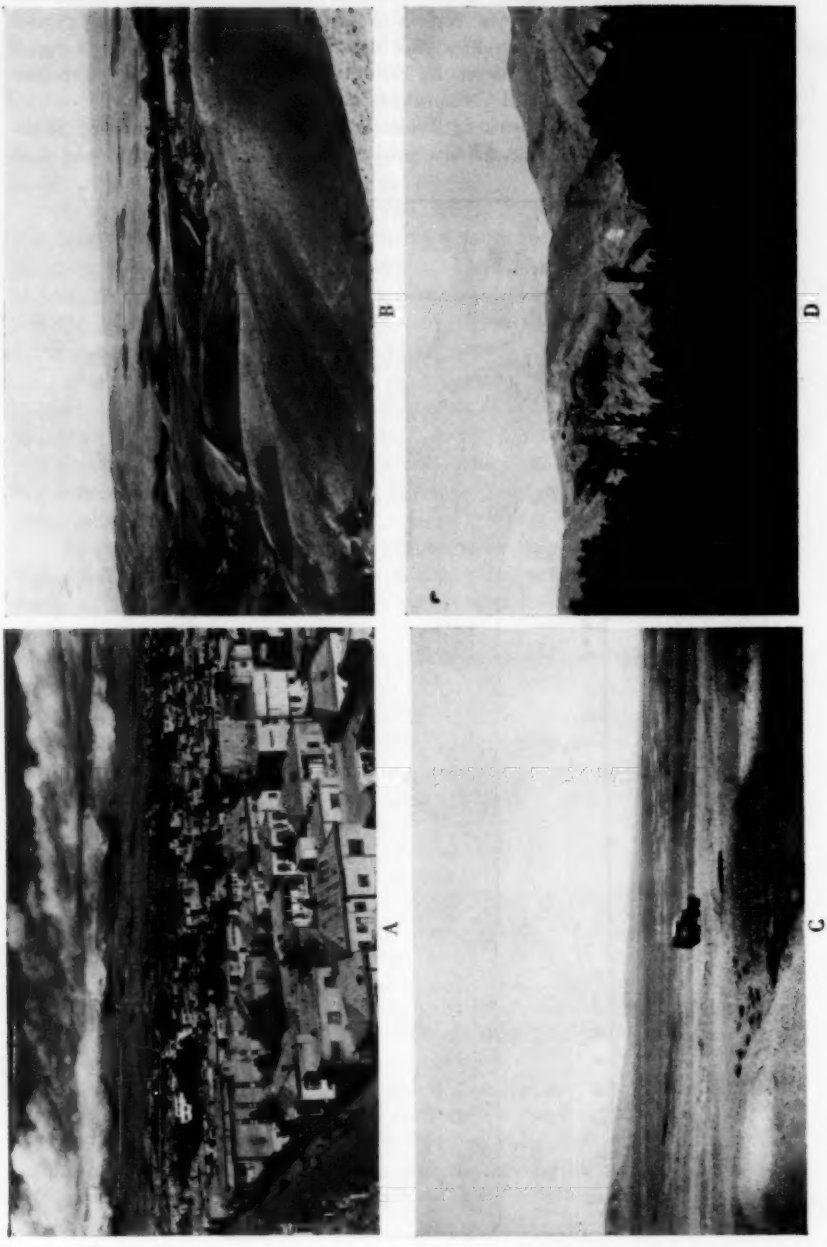


Fig. 4. A general schematic cross section N-S through the Teheran region.

PLATE 1



extend half a mile to the south. Road cuts across the promontory reveal dark-green, serpentinized volcanic tuff, belonging to the Elburz complex. These rest on brownish-red terrigenous débris identical with the red coating at the surface of nearby Pleistocene alluvial fans. In a small ravine on the western side of the hill, the same red material as well as calcareous tufa, such as is commonly found coating the subrecent débris, dips sixty degrees and more to the south (fig. 3-H).

A thrust contact dipping fifty degrees to the north can be observed between the green beds and Hezardareh débris at the opening of the main ravine between Shahabad and Sohanak, two miles west of Sohanak (fig. 3-I).

These features, along with others observed between or beyond the above mentioned localities, can be explained by a relative southward push from the Elburz range which has produced a bulging along the foot of the range. Furthermore, the asymmetry of large folds within the green beds (Rivière, 1934, p. 144) indicates that these folds have been overturned to the south. This explanation is also borne out by the presence of the anticline at the entrance of the upper Jajerud valley (cf. p. 627).

In summary, these observations show that the lower Tertiary represented by the green beds complex has been brought over the Mio-Pliocene and over some mid-Quaternary units, and even late Pleistocene deposits.

I should mention that an overthrust of the Paleogene Elburz green beds over Bakhtiari conglomerates has been observed by Dr. Frei, geologist of the Iranian Oil Co., north of Kazvin, one hundred miles west of Teheran.

MORPHOLOGY

When viewed from Teheran the panorama of the Elburz front displays a series of steps that break the regularity of the mountain slopes. Steps on the slopes of the Shemran mountain between the Jajerud valley to the east and the Kan valley to the west have definite altitudes; the surface of the steps may drop off southward, may be level or may even slant northwards. Most of these features show on the 1:100,000 map and even on the quarter-inch map, although the contours are only approximate. Details of these steps are described in table 1.

A. The Shemran mountains. Looking north-northeast towards Sohanak from northeast Teheran. In middle distance from center to right, crest of the Hezardareh hills; from center to left, low hills of folded alluvium.

B. From above Sohanak, looking southwest, toward Teheran. The nearest hills are the Hezardareh formation, subvertical or dipping to the west. In the large hill (anticlinal no. 4) left of center, the Hezardareh contains Devonian pebbles from the center of the Elburz range. To the right, hills of the Hezardareh, south of Tajrish. (Photo by courtesy of Mr. W. A. Sparwasser, soil conservationist, Chickasha, Oklahoma.)

C. From road to Semnan east of police station of Tumbakuh, 10 miles southeast of Teheran, looking east-southeast across the Veramin plain. The road is on a "lake terrace" (?) (zone XI, 3400), the prolongation of which is visible on the left in the middle distance; below, center right, are ancient pebble beaches (XII, 3330). Distant hills in the center show the Hezardareh dipping towards Veramin. (Photo by courtesy of Mr. W. A. Sparwasser, soil conservationist, Chickasha, Oklahoma.)

D. Looking west across entrance of Kan valley. Center left, deeply eroded Hezardareh anticline overthrust by Elburz green beds dipping to the north.

TABLE 1
Morphological Features

Zone	Approximate altitudes feet	meters	General aspects	Main formations involved	Local characteristics	Localities
	12,977	3840	Summit of Mount Tochal			12 miles north of Teheran.
I	11,000	3400	Break in the slopes	Elburz green beds	Regularly stratified	Upper slopes of Mount Tochal.
II	10,000	3000	Mountain tops, short crests	Volcanic masses with green beds	Rugged surfaces	South of Mount Tochal.
III	8900	2700	Lateral crests, moderate slopes		Some red soil	Shemran and Kan mountains, S.-E. & S.-W. of Mount Tochal.
IV	8200	2500			Red soil	At 10 localities in the Shemran and Kan mountains; on same level as top of Mount Arakuh.
V	7350	2250	Platforms, moderate slopes	Green beds and volcanic masses	Red soil, calcareous breccia	At 12 localities in the same mountains. On vestiges of ancient alluvial cone above Sohanak; same level as top of Sepayeh.
VI	6300	1950	Gentle slopes, lateral crests		Red soil, breccia, Kahrizak material	Shemran, along mountain front; crest of Hezardareh hills.
VII	6100	1850	Platforms, tops of outliers		Red crusts and Kahrizak material	Shemran mountain front; apex of dissected fan W. of Tajrish, tops of green beds outliers E. of Tajrish.
VIII	5750	1725	Platforms, truncated hills	Hezardareh, Kahrizak & Teheran alluvium	Same as VII; conglomerates in river terraces	Lowest platforms at foot of Elburz, flattened tops of ridges across the plain, peneplained surface in Sepayeh; 150^{m} & 100^{m} terraces in Jajerud valley.
IX a.	4750	1475	Subhorizontal conglomerates	Earlier Teheran alluvium	Terrace conglomerates	a. N. of Sepayeh (Surkh-Hessar); 40^{m} & 60^{m} terraces near Jajerud bridge.
IX b.	4100	1250				b. W. (Mashkarabad) and S.-W. (Zendan) of Sepayeh.
X a.	4100	1240	Low cliffs, bad land surfaces	Teheran alluvium	Brown-red clayey loam, with some sand and gravel	a. N. of Teheran airfield (Mehrabad).
X b.	3800	1160				b. W. of Teheran airfield (Mehrabad).
X c.	3500	1070				c. Lower margin of subrecent deposits, S. and S.-W. of Teheran.
XI	3400	1040	Protracted horizontal platform	Kahrizak or Teheran	Lake terrace [?]	From Khaniabad to Jajerud (river), along southern foot of Anti-Elburz.
XII	3330	1015	Heaps of pebbles, crescent-like	Subrecent	In one or a few regular rows	Parallel to western part of XI, S. of it.
XIII	3300	1000	Steep low cliffs and mounds	Kahrizak	Clay, loess-like deposits, bad lands	Lower margin of Kahrizak deposits, S., S.-W. & S.-E. of Teheran.
	2600	800				Playas in the kevir depressions, 40 miles S. of Teheran.

These step-like features suggest vestiges of peneplained land surfaces that resulted from variations in rate and interruptions during the uplift of the Elburz range.

Red soil characteristic of laterized subrecent surfaces is commonly present on these moderate slopes and platforms. Some places of sufficient extent, as in zones VII, VI and V, have been cultivated. At other places, on the same red soil, débris from the green beds is cemented into calcareous breccia.

River terraces, zone IX, have been mentioned by Clapp (1940, pl. 12, fig. 3), Rivière (1934, p. 75), and Bobek (1937, p. 164, pl. 17, fig. 14). These terraces have been estimated by Rivière to be respectively at 120 to 180 feet (40 to 60 m) and at 300 to 450 feet (100 to 150 m) above the river bed. They are represented by coarse subhorizontal conglomerates unconformable upon the Hezardareh; the upper ones may be late Quaternary (Kahrizak), the lower ones, probably subrecent, correspond in altitude, 4900-4700 feet (1500-1450 m), to those on either side of the highway west of the Hezardareh hills and north of the Sepayeh. Their substratum, our folded Hezardareh with local patches of discordant Kahrizak, is represented on previous maps either as "Jajerud gravel" (Clapp, 1930, p. 75, fig. 5), or "Oligocene," namely green beds (Rivière, 1934, pl. B.), with no mention of structure. Stahl on a general geological map (1897) however, gives it as Neogene; and Bobek (1937, p. 164) mentions the presence of "delta deposits dipping to the south."

Similar subhorizontal conglomerates are seen at a few places close to the western and southwestern foot of the Sepayeh at 4300 feet (1290 m) and 4000 feet (1220m).

A cliff-like margin, zone X, mentioned on p. 625, starts north of the westernmost promontory of the "Anti-Elburz" and follows the 3500 foot contour of the "Quarter-inch map" (1067 m). It can be detected as a sinuous ribbon of low mounds, eroded into bad lands to the west where it approaches the trans-Iranian R.R., southwest of Teheran. Terrigenous margins of similar aspect are seen at higher altitudes, west of the airfield at 3800 feet (1160 m), and between 4000 and 4100 feet (1220 and 1250 m); these too indicate the limit in extension of subrecent deposits.

A "terrace" of surprising regularity (XI) becomes visible from Khaniabad, eight miles southeast of Teheran, and can be seen eastwards for sixteen miles following the foot of the "Anti-Elburz" as far as the hills where the Jajerud flows out into the Veramin plain at the apex of its broad alluvial fan (fig. 1). This feature appears as three to four light brown bands of muddy ground separating a slanting alluvial surface to the north from a lower irrigated plain to the south (pl. 1-C).

Since the topography of that district has been carefully mapped on the scale of 1:10,000, with contour intervals of ten meters, "terrace XI" presents a problem. A convergence of the contours between 1030 and 1050 meters (3370 and 3430 feet), marking a six percent slope, takes place for a distance of several miles but when it approaches the Jajerud and farther eastwards a few miles beyond that river at the limit of the map, the convergence takes place between 1030 m and 1040 meters (3370 and 3400 feet). It is possible

that a recent uplift tends to warp the alluvial plain, near the opening of the Jajerud valley, where the river flows out of its cañon through the "Anti-Elburz" (p. 622).

A simpler solution may be offered by archeologists. The apparent terrace may be the remains of an aqueduct engineered sometime during the existence of the ancient city of Rhages (the present Rey) for the purpose of bringing the water of the Jajerud westward to that important city. Perhaps the engineers found it convenient to use an already existing lake terrace to facilitate their irrigation projects.

To our knowledge, no description has been given of the stages of expansion and regression of the late Pleistocene lakes, reduced now to playas and salt marshes in the ill-famed kevirs.

Fifty to sixty feet below "Terrace XI," where the plain becomes level, a succession of gravel heaps, sometimes crescent shaped, disposed locally into four to seven rows differing by a few feet in their elevation, can be interpreted as a vestige of an ancient regressing lake shore. The well-polished pebbles, originating in the Elburz green beds, increase gradually in size eastwards toward where the Jajerud had its delta in a late Pleistocene lake. These remnants of a beach with crescent-like wave-built mounds are best seen south and southeast of the police station of Tumbakuh, twelve miles southeast of Teheran, where there was a small bay at an altitude of about 3300 feet (between 1000 and 1020 m) (pl. 1-C).

The low cliffs on the road to Qum, thirteen miles south of Teheran, near Kahrizak, have been mentioned (p. 623). The highway, after following their upper rim for one mile, cuts across them to reach the lower level of the plain (Stahl, 1897, p. 43). This plain is irrigated by "kanats" that flow out from the foot of the short steep slopes which mark the southern limit of the Kahrizak deposits (fig. 4).

The cliff can be followed westward until it reaches the Trans-Iranian R.R., where it is lower, showing a tendency to turn west-southwest roughly parallel to the outcrops of the Hezadareh (p. 622), as if both formations were affected by a bulging of the Kenaregird mass. North of Kahrizak the deposits overlap part of a low ridge of andesitic tuffs. Proceeding to the east the cliff recedes gradually from outcrops of andesitic rocks and Nummulitic limestones, which are a continuation east-southeast of the first-mentioned tuffs. Near the road to Veramin low mound-like outcrops of the Kahrizak branch out in two directions. One of the forks turning southeast is visible near the bridge over the Jajerud (R.R. station of Baqirabad on the edge of the map); the other extends northeast and north, towards the foothills, to the west of the point where, at 3330 feet (1010 m), the road to Semnan passes the remains of beach south of the police station of Tombakuh. A cross-cutting boundary here separates the Veramin basin from the main portion of the Teheran plain.

GEOLOGIC HISTORY

The deposition of the continental upper Miocene or "Fars facies," and the accumulation of the Mio-Pliocene "Bakhtiari facies" (the Hezardareh of the Teheran area) reflect the tectonic activity that prevailed throughout later Tertiary times and affected, with renewed intensity, the Elburz green beds complex. This is particularly clear when we examine the Hezardareh of

the upper or northern zone of the Teheran alluvial plain.

The deposits of the upper Miocene were formed mostly at the expense of Paleozoic and Mesozoic limestones, quartzites, and accompanying plutonic or volcanic rocks from the central Elburz. Only the uppermost sandstones and conglomerates of the upper Miocene contain a small percentage of green beds fragments derived from the southern Elburz.

In striking contrast, during Mio-Pliocene time these southern Elburz paleogene green beds became, for the most part, the exclusive source of material for the Hezardareh in the northern part of the plain. It is in this Hezardareh that we have the best record of the Elburz front's long exposure to weathering.

The disappearance of all material of central Elburz origin and the exclusive presence of green beds material show the importance of the orogenic phase that raised the front range to a much greater elevation during the time of Hezardareh deposition. We can conclude that some of the streams that rose in the center of the range and had been contributing to the earlier deposition on portions of the plain were compelled to alter their courses and to become tributaries to the Karaj and Jajerud rivers, which even now bring down significant percentages of material older than the Paleogene of the green beds complex.

We can imagine that the Shemran mountains were then hills of moderate elevation rising above the alluvial plain in the same manner as the upper portion of these mountains now stand above levels I, or I and II, referred to above. The green beds predominated in those hills, as in the upper portion of the mountains now. They are represented by gravel in most of the typical Hezardareh layers. The rate of elevation was moderate enough to allow rivers from farther north to cut through the mountains which did not present a greater barrier than do the low ridges of the present-day alluvial plain.

Before the deposition of the Hezardareh the upper Miocene was locally affected by movements (p. 627). These movements may have been contemporary with the early intrusions and extrusions of red andesitic magma abundant to the south and southwest of the plain. An important phase of that late tectonic activity deformed both formations in post-Pontian time.

The erosion that affected the rising ridges of Hezardareh supplied material to antecedent streams. These streams transported their load farther to the south, where the resulting deposits must be hidden now in the depressions of the kevirs, which were partially filled by those deposits.

As already stated (p. 626), because of the lack of fossils more data are needed to enable us to decide where in the post-Pliocene the Kahrizak deposits should be assigned. We think that they had been washed down from the Elburz after a long period of deposition indicated by the eroded surface of the Mio-Pliocene on which they rest and by the alluvium of the kevirs.

The heterogeneous material of the Kahrizak indicates a relatively cool period (Bobek, 1937, p. 180) immediately following renewed orogenic activity. During this period some of the most massive layers, sills, or extrusions within the folded green beds complex formed because of their resistance to erosion huge obstructions that stood as temporary dams across the rejuvenated transverse valleys. Catastrophic outwash would result when these dams yielded. Ruins of such dams are found in several places on the Shemran old alluvial

fans. One manifests itself as a swarm of gigantic blocks at the opening of a valley east of Darake, two and a half miles west of Tajrish. Thick mudflows carried away many of those blocks, some of which were left at the mouth of the valley and some along the upper course of the stream where they are visible now as coarse, sub-horizontal deposits lying discordantly on the tilted Hezardareh. Other blocks were transported a few miles to the south. Below Wilanjak, west of Tajrish, the largest block I know of has a volume of at least sixty cubic meters (Rivière, 1934, p. 75-76; Rieben, 1935, p. 51-52; Bobek, 1937, p. 164). A preserved, but silted up, natural dam of this type is still conspicuous one mile above Farahzad (eight miles northwest of Teheran), closing the narrow V cañon a short distance above its opening.

WATER RESOURCES

At the time of World War II the need for ground water to supply occupation forces became urgent. For practical reasons two types of alluvium were considered as sources: (1) the water-bearing recent and subrecent deposits, and (2) the underlying, generally tilted gravels previously considered as too compact, impervious, and dry to produce water.

The limited geological investigation that we started proved that most of the ground water is present in those deeper, tilted gravels of the Hezardareh.

The basin-like form of the Hezardareh deposit, the prevailing dip of its upper and thicker portions, its extension under the city area, and the number of poorly consolidated beds it contains make it a valuable ground-water reservoir, protected from contamination by the presence of an impervious kaolinized capping and by the clayey deposits present at the base of the overlying alluvium.

Some sixty years ago a deep well had been drilled (Stahl, 1897, p. 2) in the compound of the American Mission. The expectation of obtaining flowing artesian water was vain, but the presence of pure water confined some 150 feet below the streets of a sewageless community was proved. In fact since World War II, deep wells, including more than one hundred drilled between 1950 and 1953, have successfully tapped that reservoir in and close to Teheran, to provide water for public, private, and industrial use. Some of the wells near Rubatkarim and Rey have proved to be artesian or semi-artesian. This might have been expected because the main recharge area is near the foot of the Elburz and along the Hezardareh hills at elevations between 5000 and 6000 feet (1525 and 1830 m), while the altitude of Rey is 3500 feet (1150 m).

The water of the artesian well at Hezarsathi eight miles northwest of Rubatkarim contrasts by its relative softness with that of numerous springs in the marshy neighborhood which contribute to the Abesiah, a slightly brackish perennial stream. The well probably reached gravels of the Hezardareh charged with infiltrations from the Karaj river which flows out into the plain at an altitude of nearly eight hundred feet above the Abesiah. The springs are probably fed by shallow aquifers located near the base of the Kahrizak formation which here overlaps on the salt-containing upper Miocene (fig. 3-A[a]).

Until forty years ago, before the industrial development started, Teheran's population of about 200,000 was satisfied by twenty to thirty "kanats" draining mainly Quaternary alluvium and partly fed by streams from the Shemran

mountains and from the Kan river. About twenty years ago an aqueduct from the Karaj river, with a capacity of three to four cubic meters a second, doubled the water available to the city. By 1940 the population passed the 500,000 mark. A modern pipe line system, now being completed, is to tap again the Karaj river, at the expense, it is to be feared, of the agricultural needs of the lower part of the plain irrigated by that water. An important problem that must be taken into consideration is that of soil and water conservation since the underground reservoir which is Teheran's most precious water supply may be depleted before the construction of the Lar water project, to tap a river draining the area of Mount Demavend and flowing north to the Caspian.

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* Note. Clapp's articles have excellent figures of the region, showing the Shemran mountains, alluvial plain with kanats, Jajerud terraces, and Miocene conglomerates.

Topographic Maps

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* "Tehran" is a semi-official spelling for Teheran.

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POSTGLACIAL FORESTS IN SOUTH CENTRAL AND CENTRAL BRITISH COLUMBIA

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ABSTRACT. Pollen analysis of 25 peat sections, from the interior of south central British Columbia and central British Columbia and along the Hart Highway, reveals a significant chronological correlation with the thermal maximum as recorded in postglacial sedimentary columns from south central Oregon and eastern Washington. The presence of a volcanic ash stratum in the sections of south central British Columbia at a stratigraphic position enclosed by the xerothermic interval as recorded in the pollen profiles is consistent with the same relationships in the Washington columns. The age of the ash in the Washington sections was originally dated at 6000 years. The radiocarbon date of about 6500 years for the eruption of Mount Mazama in southern Oregon, and the similar relationship of the pumice from this eruption as shown by its stratigraphic position in peat sections to the recorded xerothermic interval suggest that these volcanic eruptions were not far apart in time. The thermal maximum in south central British Columbia is depicted by an expansion of ponderosa pine and grasses, chenopods, and composites sometime after organic sedimentation was initiated and well before the present. The postglacial thermal maximum may have occurred about 6000 years ago, with the xerothermic interval lasting from 7500 to 3500 years ago.

During the summer of 1947 a transect of 14 peat sections was obtained from as many sites of organic sedimentation in the intermountain region of south central British Columbia, along the Cariboo Highway northward to Prince George, and west along the main highway to Hazelton on the Skeena River (fig. 1). Twelve additional sedimentary columns were obtained during the summer of 1952 along the Hart Highway, connecting Prince George and Dawson Creek, the southern terminus of the Alaska Highway, a distance of about 265 miles. All the sections obtained in 1947 and one obtained in 1952, that closest to Prince George, lie within the Fraser River drainage. The other 11 along the Hart Highway lie within the Peace River drainage, of which six are in the Parsnip River basin which drains northward into the Peace River, three lie in the Pine River valley on the east slope of the Rocky Mountains, and two, nearest to Dawson Creek, lie in the Kiskatinaw River drainage.

Pollen analyses of sedimentary columns from these bogs reveal an interesting and significant postglacial forest sequence in the adjacent areas within range of pollen dispersal. The transect cuts across several distinct phytogeographic provinces as well as the range limits of several important arboreal indicator species. Postglacial expansions and contractions of these species as recorded in the pollen profiles reflect climatic trends during the time represented.

The southernmost section was obtained from a large sedge meadow between the towns of Merritt and Princeton, about 20 miles north of the latter (fig. 1). The northwesternmost was taken from a vast muskeg-type floodplain

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Fig. 1. A somewhat generalized map of British Columbia showing the sites of bogs and approximate ranges of forest trees that are represented by pollen in the sedimentary columns. Range limits of trees are taken from Whitford and Craig, 1918.

bog a few miles east of Houston and about 80 miles southeast of Hazelton. The northeasternmost sedimentary column was taken from a muskeg 19 miles west of Dawson Creek. Coincidentally, each of the two northernmost bogs lie about 450 miles in a straight line from the southernmost and about 250 miles from each other.

The thicknesses of the sections vary from 1.0 to 7.5 meters. This includes varying thicknesses of clay or silty sediments underlying the peat which may or may not contain pollen grains. A section taken from a vast sedge marsh between the towns of Vernon and Kamloops extends down to bedrock, but in boring most sections sand or gravel was reached. All but six of the bogs were developed in basins occupied by lakes as evidenced by an abundance of aquatic plant pollen in the lower levels. The other six, including those in the Fraser River drainage located 5 and 15 miles southeast of Prince George, and those located 19, 40, 71, and 90 miles respectively west of Dawson Creek, were developed on more or less flat terrain and are similar to the muskeg type found farther north, which are often underlain with permafrost or a frost

residuum, depending upon their latitude (Hansen, 1950; 1953). A frost residuum was encountered only in a muskeg located 19 miles west of Dawson Creek and this in August. Topographic evidence that these six muskegs were not initiated in standing water is supported by the absence of aquatic plant pollen in the lower levels and by the presence of ericaceous pollen and Sphagnum moss spores in the sediments immediately overlying the blue clay at the bottom of the section. Six sections, four from the Fraser River valley and two along the Hart Highway, were obtained from sedge bogs on which the predominant vegetation consists of sedges, rushes, and cattails, and other species common to wet meadows or marshes formed on floodplains or in shallow ponds and lakes.

The other bogs support typical bog flora including *Sphagnum* spp., several species of ericads, bog birch (*Betula glandulosa*), *Rubus chamaemorus*, *Empetrum nigrum*, *Eriophorum* spp., and black spruce (*Picea mariana*). Only two of the bogs in the Fraser River Valley south of Williams Lake support spruce, which was identified as Engelmann spruce (*P. engelmanni*). These are located south of the range of white and black spruce in interior British Columbia. In this drier area Engelmann spruce has apparently found a favorable habitat on the bogs, as it is absent from adjacent higher slopes. In fact, the open slopes adjacent to the bog two miles south of Clinton support both juniper (*Juniperus scopulorum*) and sage (*Artemisia tridentata*). Tamarack (*Larix laricina*) occurs on the five muskegs lying on the east slope of the Rockies. This species is a member of the boreal forest that extends north and west from New Foundland into the Yukon Territory.

In the preparation of the sediments for microscopic study, the potassium hydrate method was used, with gentian violet as the staining medium and glycerin jelly for mounting. From 100 to 200 tree pollen grains were identified from each level. Insufficient pollen was recovered from a section 40 miles west of Dawson Creek for a diagram, but the proportions for the several species were consistent with adjacent sections. It was soon apparent that at least two species of pine pollen were present, and use of the size range method resulted in the separation of those that lie within the size ranges of lodge pole pine (*Pinus contorta*), western white pine (*P. monticola*), and ponderosa pine (*P. ponderosa*) as determined by the author (Hansen, 1947). At least three, and possibly five, of the sites of sedimentation lie within the present range of ponderosa pine. Although the relative size ranges of black and white spruce (*Picea glauca*) pollen indicate that they may be separated (Potzger, 1953), no attempt was made to do this. In the region of this study, the 20 northernmost bogs lie within the ranges of white and black spruce, and all of them within the range of Engelmann spruce (fig. 1). The proportions of spruce pollen in most of the sections are not great, and it seems doubtful if separation of the three species would prove to be of any significance.

Volcanic ash occurs in 13 of the sections. In the 4 southernmost sections the ash is present in a fairly well-defined layer, while in all others except the two nearest Dawson Creek, the glass fragments are scattered in the peat matrix. It is probable that ash is present in all the sections, but samples taken at 2-decimeter intervals evidently omitted the stratum of peat with the

scattered glass. Unless a well-defined layer is present, it is not possible to find the glass fragments until microscopic examination is made. This is especially true in limnic peat, where the sediments often are light colored like the ash. The origin of this volcanic material is problematical because of the widespread occurrence of volcanic ejecta in postglacial sedimentary columns in the Pacific Northwest, western Canada, and Alaska. It seems probable that the ash in south central British Columbia is from the same source as a well-defined layer consistently occurring in Washington peat sections (Hansen, 1947). In 10 sections taken in the northern half of eastern Washington this ash stratum occurs at a stratigraphic position at which the pollen spectrum records the postglacial thermal maximum, which is also true in some of the sections of this study. The source of the volcanic glass is probably Glacier Peak in north central Washington, whence it has been traced eastward on Late Wisconsin drift (Waters, 1939). The ash in the sediments becomes thicker to the east and north suggesting that strong southwest winds were in force at the time of the eruption and that the finer components were most abundant. The distance from Glacier Peak to the southernmost site of this study, between Merritt and Princeton, is about 120 miles, which is less than from the peak to bogs in northeastern Washington where the ash is several inches thick. The presence of only one ash horizon in the postglacial sediments of this region and its position close to the thermal maximum as denoted by the pollen profiles makes it reasonable to assume that it is from the same source. One or more ash horizons were noted in many sections along the Alaska Highway in northeastern British Columbia, the Yukon Territory, and Alaska (Hansen, 1950; 1953). Most of these are near the surface suggesting recent deposition. The volcanic glass near the top in the two sections near Dawson Creek may have had the same source as those along the Alaska Highway (fig. 8-A, D).

VEGETATION OF THE REGION

The vegetation of the region within range of pollen dispersal to the sites of the sediments varies greatly. The region south of Quesnel, from about the 53rd parallel southward to the boundary of the United States and between the Coast Range and the Rocky Mountains is covered with grasslands, savanna, and open forest because of the dryer climate caused by the rain shadow cast by the Coast Range. Before the advent of white man and agricultural development, it is estimated that over 3,000,000 acres were occupied by grassland (Tisdale, 1947). These grasslands occur in the larger and lower valleys and adjacent slopes to an altitude of 3000 to 4000 feet depending upon slope and exposure. The open forest interfingers into the grasslands where moisture and exposure afford more mesic conditions. The annual precipitation in the dryer, southern interior ranges from about 7 inches at Ashcroft to over 16 inches at Quesnel at the northern limit of the grassland region. In the lower and dryer areas of the grassland such xeric indicators as *Artemisia tridentata, A. frigida, Purshia tridentata,* and *Chrysothamnus nauseosus* are present. On alkaline areas *Sarcobatus vermiculatus, Salola kali tenuifolia, Chenopodium album, C. fremontii, C. humile, Atriplex argentea,* and *Salicornia europea* occur. The most common native grasses of the southern interior of British

Columbia are *Agropyron spicatum, Poa secunda, Festuca idahoensis, F. scabrella, Stipa commata, S. columbiana, Koeleria cristata,* and *Sporobolus cryptandrus.* The introduced species, *Bromus tectorum,* is also common in areas that have been overgrazed and repeatedly burned. Six of the sections are located within the grassland region, and the importance and significance of the grasses, forbs, and shrubs of this xeric area are reflected in their pollen profiles. The proximity of the open forests on the higher adjacent slopes and the denser more mesic forests on the upper slopes, both to the east and west, however, is reflected in the sedimentary columns due to the greater amount of windborne pollen derived from the arboreal species. The relative expansion and contraction of grassland and forest attributed to climatic fluctuation are reflected in the profiles of the several sections.

As stated before, the transect of sections traverses the range limits of certain arboreal climatic indicators. The most important of these is ponderosa pine, whose northernmost limits occur a few miles north of Clinton in the vicinity of Chasm (fig. 1; Whitford and Craig, 1918). Western white pine likewise is restricted to the southern part of interior British Columbia, but its range extends northward somewhat farther on the west slope of the Coast Range and in the Rockies to the east, occupying the higher slopes where there is sufficient moisture. Whitebark pine (*Pinus albicaulis*) also occurs on the dryer upper slopes, largely within the range of white pine but much more sparsely. Lodgepole pine, predominantly represented in the sedimentary columns, is the most common and widespread conifer in the region. It is the most xeric forest tree species next to ponderosa pine, also thrives on poor soil, and invades at the expense of others where fire has occurred. It becomes sparse on the higher slopes of the Coast Range where there is more moisture and northward where it suffers more competition from spruce and aspen (*Populus tremuloides*).

The range of Douglas fir (*Pseudotsuga taxifolia*), recently changed to *P. menziesii,* which is represented in most of the sections, encloses the sites of all the sediments except the six on the eastern slope of the Rockies. It is most abundant in the southern and eastern part and thins out northward to an occasional tree where local conditions are favorable. The only species of fir whose range is coextensive with all the sites of sedimentation is alpine fir (*Abies lasiocarpa*). Lowland white fir (*A. grandis*) occurs only in south central British Columbia but extends farther northward on the lower west slopes of the Coast Range. An occasional specimen was noted in the vicinity of the Merritt section. Silver fir (*Abies amabilis*) is absent in interior British Columbia, but is abundant on the west slopes of the Coast Range and extends northward to southeastern Alaska. Noble fir (*A. procera*) is present only in southwestern British Columbia.

Four species of spruce occur in British Columbia. In this study Sitka spruce (*Picea sitchensis*) is unimportant because it is confined to the southwestern part of the province and ranges northward along the coast into Alaska to Cook Inlet. It is possible that this species is represented in the Merritt section since it occurs within 25 miles to the west. The only spruce whose range encloses all the sites of this study is Engelmann (*P. engelmanni*)

which occurs on the east slope of the Coast Range northward through Hazelton almost to 58° latitude, and then ranges eastward and southeastward through the Rocky Mountains. Black spruce ranges south to Quesnel while white spruce extends somewhat south of Prince George in the interior (fig. 1). The twenty northernmost sections lie within the ranges of black and white spruce. Extensive pure stands of white spruce occur along the Hart Highway in the mountains.

The range of western hemlock (*Tsuga heterophylla*) which is sparsely and sporadically represented in most of the interior sections occurs in the Coast Range to the west and on the west slope of the Rockies. A few specimens were noted within 50 miles of the northwesternmost section. Mountain hemlock (*T. mertensiana*) which is represented more sparsely than western hemlock has somewhat the same range as the latter but at higher elevations. Western red cedar (*Thuja plicata*) has a range similar to that of western hemlock, but it extends across the southern part of the province to connect the eastern and western belts. Western larch (*Larix occidentalis*) is restricted to the southeastern part of the province where it is more or less coextensive with ponderosa pine but at higher elevations. As stated previously, tamarack (*L. laricina*) is a member of the boreal forest which extends across the continent. It is confined to bogs and muskegs except at the northern limits of its range where it occurs on higher ground. Pollen of *Larix* apparently is not well preserved in peat, and thus its record is absent. It is evident that only three species of conifers, lodgepole pine, alpine fir, and Engelmann spruce have ranges which in general are coextensive with all the sites of sedimentation of this study.

The two most important and widespread broadleaf arboreal species are aspen (*Populus tremuloides*) and northern black cottonwood (*P. trichocarpa hastata*). Aspen thrives as a result of fire, and it will largely replace lodgepole pine if the pyric influence is strong and often repeated. The black cottonwood occurs mostly on floodplains in the southern part of its range, but it becomes an upland species under moister conditions northward. Extensive stands were noted along the Hart Highway on the east slope of the Rockies. White alder (*Alnus rhombifolia*) ranges into south central British Columbia where it occurs chiefly along stream courses, and its pollen occurs in the peat sections from this area. None of the sites of sedimentation lies within the range of red alder (*A. oregona*) which is confined largely to the coast and coast mountains, extending northward into Alaska. It was noted in the Hazelton region, which is probably about as near as it occurs to any of the bogs of this study. The range of western birch (*Betula occidentalis*) and its varieties is not well known in British Columbia. It was noted as being locally abundant along the Fraser River south of Prince George and in the vicinity of Hazelton. It was not abundant along the Hart Highway, although on the east slope of the Rockies white birch was locally present. It is probable, however, that the birch noted here was *Betula papyrifera* or one of its varieties. Birch is only sparsely represented in the sedimentary columns and its pollen is probably mostly that of bog birch (*B. glandulosa*).

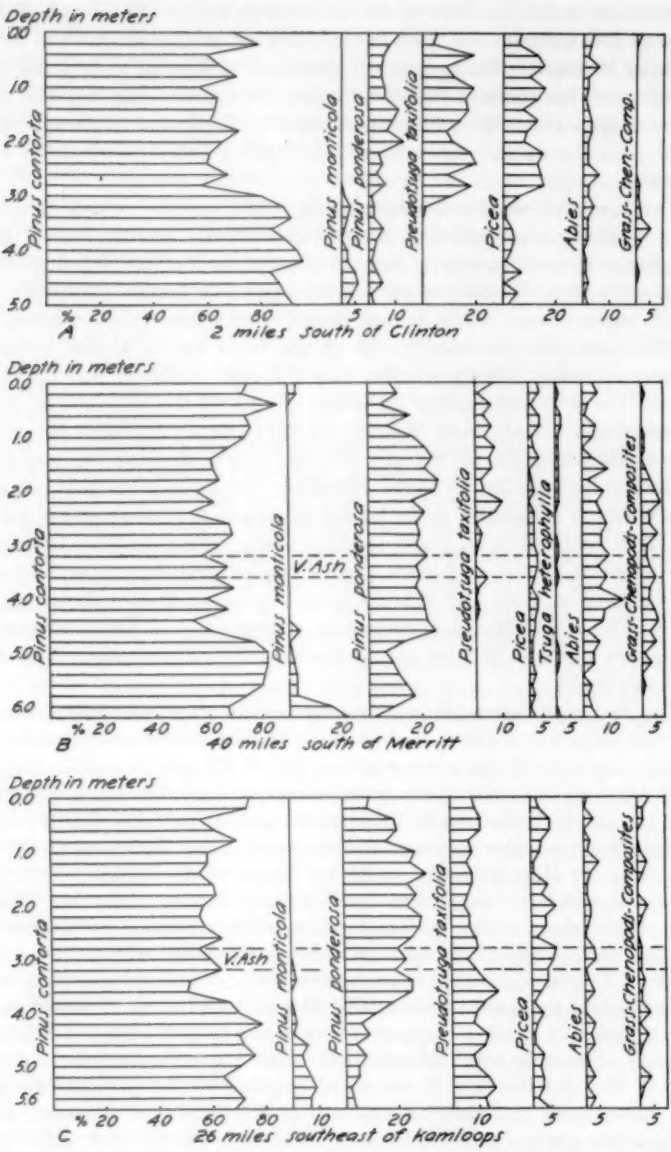

Fig. 2. Pollen diagrams from the three southernmost sections, showing prominence of ponderosa pine and significance of grasses, chenopods, and composites in relation to the volcanic ash horizon, which probably marks the time of the thermal maximum in south central British Columbia.

POSTGLACIAL VEGETATION

Lodgepole pine is the most abundant species in all the 25 sections, being recorded to well over 50 percent at most levels (figs. 2-8). In fact, at very few horizons is it superseded by other species, and it has an average of over 60 percent throughout and about 83 percent at the lowest level. The most consistent trend of lodgepole is a general decline upward in the profiles to a point somewhere in the middle third of the sections. This occurs in 17 of the 25 sections. From this minimum, the trend is a general increase to or near the uppermost horizon. Most of the sections reveal an increase in the top level, which is probably to be associated with the advent of white man and the attendant modification of the environment through burning and deforestation which has been favorable for lodgepole. Although lodgepole is predominantly represented in the lower levels of most postglacial sedimentary columns in the Pacific Northwest, it was rapidly replaced by longer-lived and more shade-tolerant species as the physiographic conditions in the wake of retreating ice were stabilized and the mineral soil modified (Hansen, 1947). In the Puget Lowland of western Washington, Douglas fir was able to crowd out the smaller and shorter-lived lodgepole, and hemlock also increased, especially after the postglacial thermal maximum. In eastern Washington lodgepole was not initially so abundant as farther west but declined more slowly and has remained more abundant than west of the Cascades. Grasses, chenopods, and composites partially replaced lodgepole as the climate became warmer and dryer and in turn were replaced by ponderosa pine as cooler and moister conditions prevailed. In south central and west central Alberta lodgepole pine was generally predominant during postglacial time (Hansen, 1949; 1949a). Here its chief competitor was spruce, which apparently was able to supersede it for brief periods. The present abundance of aspen suggests that it played an important role in succession after fire, though poor preservation of aspen pollen in peat largely conceals its history. Farther north in Alberta, spruce and lodgepole have competed equally, and still farther north along the Alaska Highway in northeast British Columbia spruce has been more abundant (Hansen, 1950; 1952). Likewise along the Alaska Highway in the Yukon Territory, lodgepole and spruce competed for predominance, with the former somewhat favored in sections as far as milepost 931 about 15 miles beyond Whitehorse (Hansen, 1953). Lodgepole then becomes sparsely represented in sections along the Alaska Highway to the Alaska border, while in interior Alaska, pine pollen occurs only sporadically. Pollen profiles from southeastern Alaska show that lodgepole was predominant in the lower levels in some sections and in the upper horizons in others, while still others show that it was superseded throughout by Sitka spruce and western hemlock (Heusser, 1952). The initial postglacial invasion of lodgepole is assumed to have been on deglaciated terrain while its expansion in more recent time is attributed to its development on the muskegs. In the region of this study, however, the record of lodgepole represents its upland succession and it would seem that conditions have been favorable for this species during the entire postglacial. Both soil and climate, as well as fire, have favored it over its competitors, as none of the climax species in either the southern or northern sectors has been able

to supersede it to any appreciable extent during the time represented by the sediments.

A significant proportion of pine pollen in the lower levels of five of the southern sections was identified as that of western white pine by the size range method (figs. 2, 3). Although error is possible with this method, the occurrence of western white pine in this area in early postglacial time is consistent with

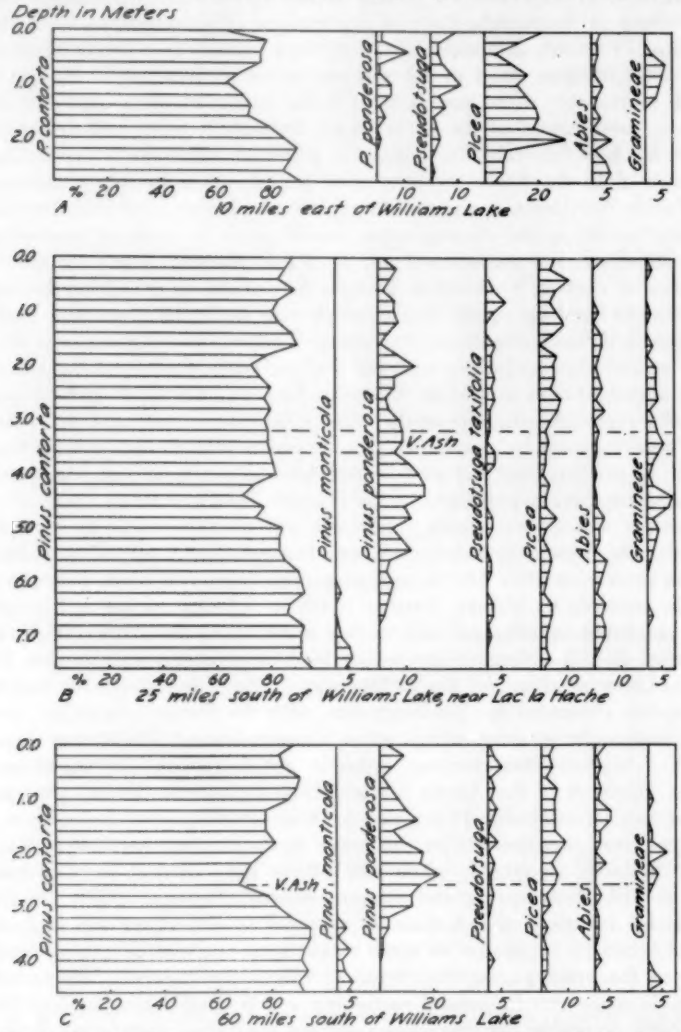

Fig. 3. Pollen diagrams from bogs south and near Williams Lake showing the ponderosa pine and grass maxima near the volcanic ash horizon. Decline of white pine and Douglas fir reflects their decreasing abundance northward in the region.

its present range and the fact that this species thrives in a moister climate such as must have existed for some time after the ice receded. In most Washington peat sections, white pine reveals its strongest record in the lower levels although it is present in low proportions throughout (Hansen, 1947). Its apparent absence in sections farther north suggests that it was unable to invade

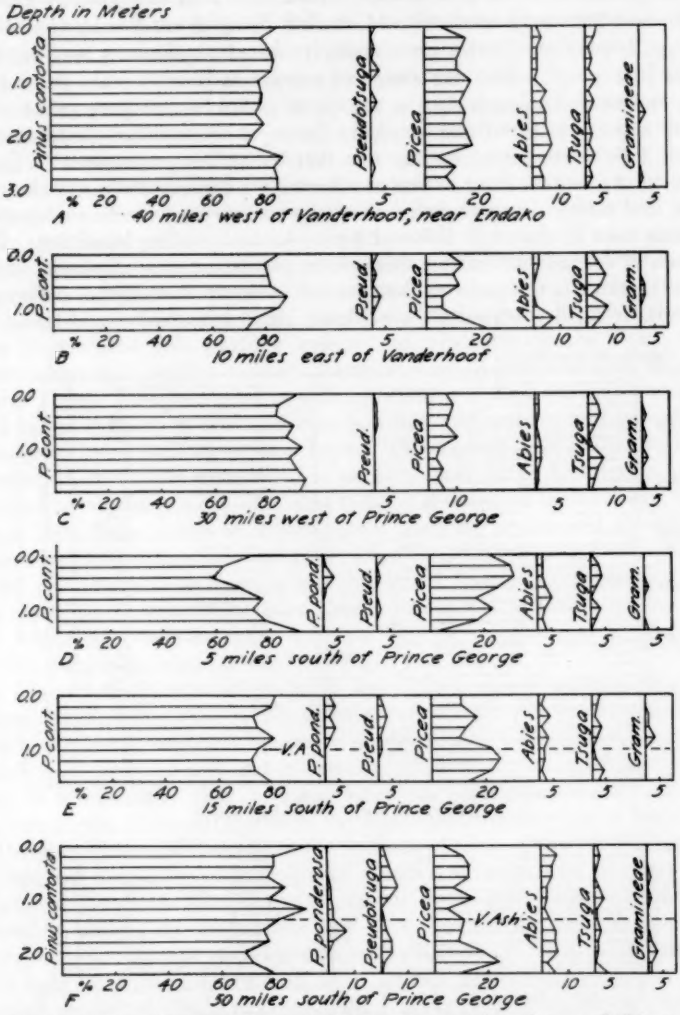

Fig. 4. Pollen diagrams of six shallow sections south and west of Prince George showing predominance of lodgepole pine throughout and absence of ponderosa pine west of Prince George. The presence of hemlock reflects the moister climate toward the coast and at higher elevations.

the dryer interior during early postglacial time, even under the moister and cooler conditions that must have prevailed.

Perhaps the most significant pollen record in the southern sector of this study as far as postglacial climate is concerned is that of ponderosa pine. The strongest record occurs in the five southernmost sections, all of which lie within the present range of this species (figs. 2, 3). It is also sparsely recorded in the next four sections northward, the last being about 5 miles from Prince George, beyond the known present day range of ponderosa pine (fig. 4-D). While it is possible that the range of ponderosa pine is more extensive in interior British Columbia than is known, its pollen record gives evidence that it was more widespread and abundant during the postglacial xerothermic interval. This is supported by the fact that its higher proportions in general occur in the middle third of the profiles with a general decline in the upper levels, indicating that postglacial warming and drying reached a maximum at some time in the past, followed by cooler and moister conditions. If the stratum of volcanic ash cutting through the ponderosa pine maximum in three of the sections is the same as that present in many Washington sedimentary columns, it further supports the evidence that expansion of ponderosa pine

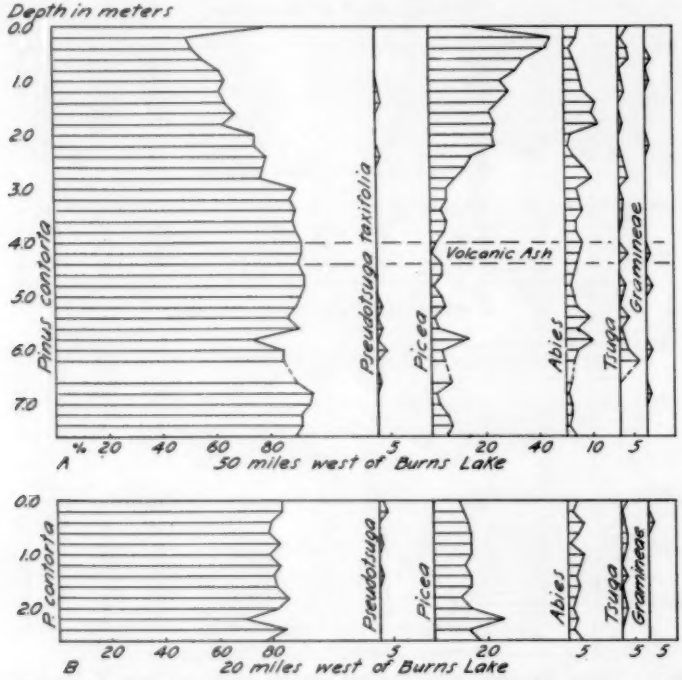

Fig. 5. Pollen diagrams west of Burns Lake, showing predominance of lodgepole pine, absence of ponderosa pine and only trace of Douglas fir. Volcanic ash may be from Glacier Peak in north central Washington.

in this area occurred in response to the xerothermic interval. In the Washington sections, the ash occurs at or near the maximum of grasses, chenopods, and composites, which is interpreted as expressing the thermal maximum in this region.

The record of grasses, chenopods, and composites is parallel to that of ponderosa pine in that their greatest proportions occur in the middle third of most of the sections (figs. 2, 3, 4, 5). In the three southernmost sections the three groups are represented, while only grass pollen was noted in those to the north. Along the Hart Highway in only two, those nearest to Dawson Creek, was grass pollen noted, although the occurrence of an occasional grass pollen is hardly sufficient to use as a basis for postulating climatic trends (fig. 8-C, D). It seems probable, however, that grasses are considerably underrepresented in sections from bogs in the grassland area, because in the upper horizons they are not recorded or only to a few percent. This is well borne out by postglacial pollen profiles in the grasslands of eastern Washington and Oregon, where in certain sections located many miles from present-day forests, tree pollen is predominant over that of grass in the upper levels (Hansen, 1947). In 17 peat sections along the Alaska Highway in British Columbia, grass is recorded only sparsely and sporadically, even in the Peace River region where soil profiles indicate a prairie flora of long standing. In south central Yukon, however, grass is well represented in four sections northwestward as far as milepost 666, and then becomes only sparsely and sporadically represented in sections as far as milepost 724 (Hansen, 1953). Paradoxically, however, it is not well represented in sections from the parkland area west of Whitehorse, where grass is abundant today. Likewise, in the Grande Prairie-Lesser Slave Lake region of Alberta, grass is poorly represented although the present parkland and prairie soil profiles indicate that grass has been abundant in the past. In peat sections in the vicinity of Edmonton, Alberta, grasses, chenopods, and composites are well represented, and at a stratigraphic position which corroborates other evidence for the existence of a postglacial thermal maximum (Hansen, 1949; 1949a).

Douglas fir is represented in all but the seven peat sections, nearest to Dawson Creek (figs. 2-8). It reveals its strongest record in the three southernmost sections and becomes weaker to the north and west. Its most consistent record is in the Vernon-Kamloops section, while it attains its highest proportions in the section near Clinton, where it supersedes both spruce and ponderosa pine at several horizons. No significant trends occur in the profiles of Douglas fir and no correlations with those of other species represented are evident that would depict a reciprocal relation influenced by climatic trends or other factors controlling forest succession. In the grassland sector of British Columbia, apparently the climate was never sufficiently moist to encourage its expansion, although its belated appearance in the Merritt and Clinton sections may have been a response to a moister climate since the postglacial thermal maximum (fig. 2). Douglas fir has not been postglacially abundant east of the Cascades in Oregon and Washington. In north central Washington and northern Idaho it has played an important role in the postglacial forests, but not to the extent it has in the Puget Lowland. In the former region its

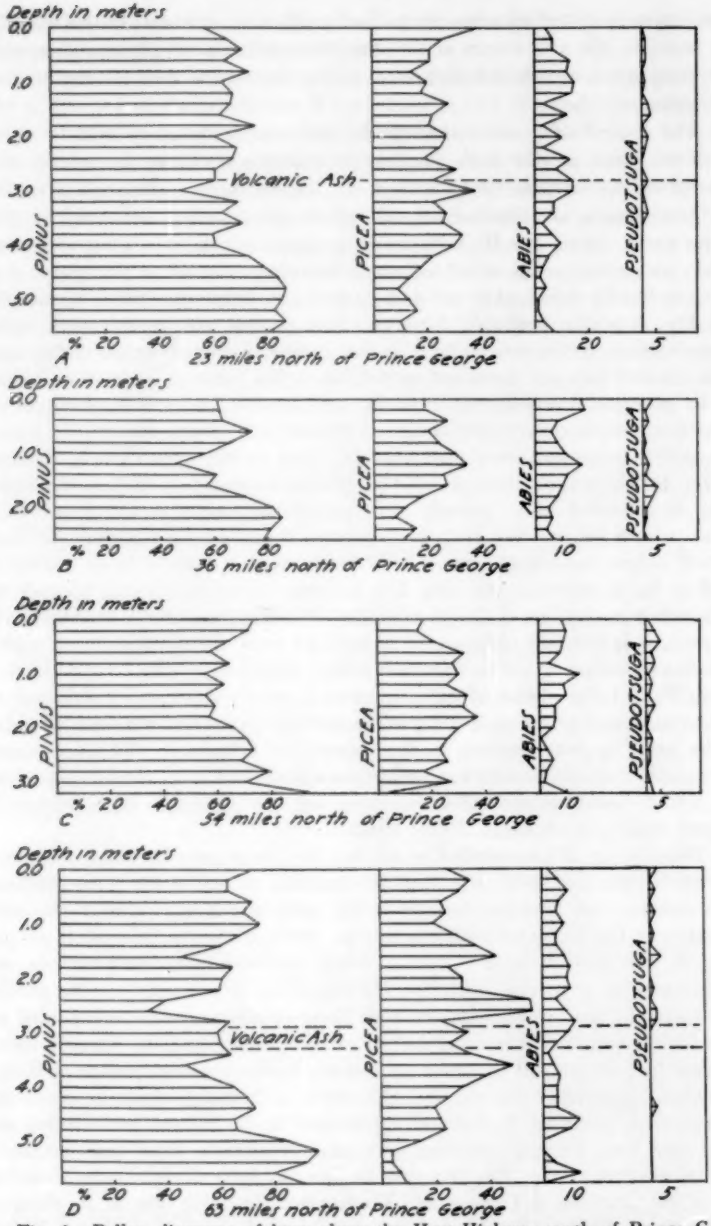

Fig. 6. Pollen diagrams of bogs along the Hart Highway north of Prince George showing predominance of lodgepole pine, and increasing importance of spruce under the moister and cooler climate. Douglas fir pollen was probably carried in from the south and west.

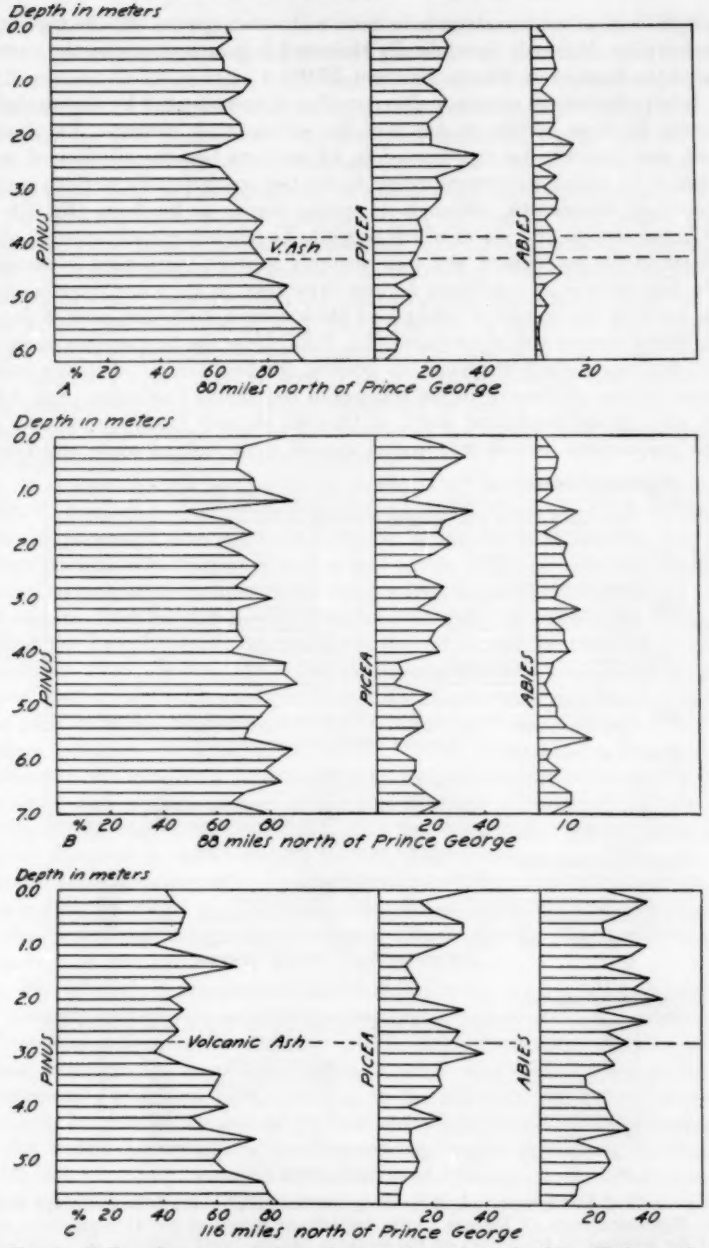

Fig. 7. Pollen diagrams of three deep sections along the Hart Highway showing predominance of lodgepole pine on gravelly mineral soil. C shows the highest proportions of fir in all sections, reflecting the montane position of the sites of the sediments.

phytosociological relationships have been with other species than in the Puget Sound region. It is only sporadically recorded in peat sections on the eastern slope of the Rockies in Alberta (Hansen, 1949).

Interpretation of spruce pollen profiles is complicated by the probable presence of three species in many of the sedimentary columns. Engelmann spruce may possibly be represented in all sections because all sites of sedimentation lie within its present range. In the two southernmost sections spruce is sparingly represented, although no spruce occurs on the bogs (fig. 2). In the Clinton section, the site of which supports Engelmann spruce, spruce pollen is absent in the lower third, and then abruptly appears, suggesting its invasion of the bog surface as conditions became favorable. In the other three sections from south of the ranges of white and black spruce, only that near Williams Lake shows spruce well represented (fig. 3-A). Here the bog surface supports a well-developed stand of spruce. In general, the proportions of spruce pollen become greater northward in the transect of sedimentary columns (figs. 4-8). Most sites of sedimentation north of Quesnel support black spruce and the pollen proportions include this species as well as the upland white and Engel-

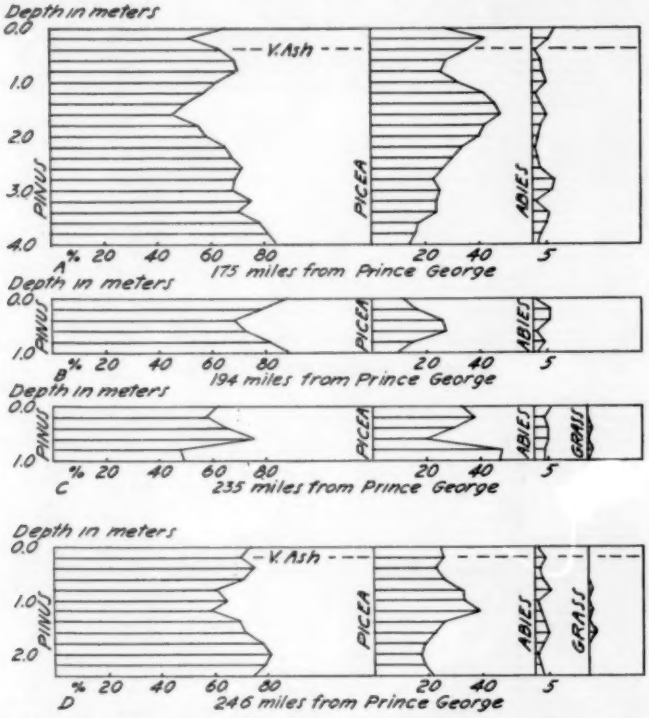

Fig. 8. Pollen diagrams from bogs along the Hart Highway, on the east slope of the Rocky Mountains, west of Dawson Creek. Increase of spruce at the expense of fir may reflect the presence of the former on the muskegs and the lower elevation. Volcanic glass is probably from the northwest rather than Glacier Peak to the south.

mann spruce. The strongest representation of spruce is along the Hart Highway where it attains proportions of over 40 percent and is consistently recorded to 20 percent or more (figs. 6-8). The fluctuations of spruce are largely converse to those of lodgepole, which suggests the possibility that one species may have increased in abundance while the other remained stable, and yet is recorded as having declined. For this reason, the level-to-level fluctuations cannot be considered as too significant in interpreting successional trends. Many of the spruce profiles reveal a maximum in the middle third which is not consistent with the maximum of ponderosa pine in the southern sections, because the latter has been interpreted as an expression of the thermal maximum. It seems probable, however, that the complementary fluctuations of spruce and pine reflect the influence of fire. Recurring fire is favorable for lodgepole because of seed retention in the cones until the heat of a fire causes them to open, shedding many years of seed. The early pollen-bearing characteristic of lodgepole causes it to be strongly represented in peat in comparatively a few years after a holocaustic fire. In the absence of fire spruce, as a climax species, was able to expand until another series of fires.

It is possible that spruce pollen in the lower horizons, especially in the southern sections is that of white spruce, as it must have migrated northward from its proglacial sites after the recession of the ice. It is possible also, that spruce postglacially reinvaded central and northern British Columbia from the north and east, as there is evidence that ice-free, forested areas persisted along the eastern flank of the Rocky Mountains in Alberta and British Columbia during the Late Wisconsin glaciation as well as in west central Yukon (Hansen, 1950; 1953; Hultén, 1937). In 16 sections studied, spruce declines in the upper level or two while pine increases. This same relationship between spruce and pine exists in 51 other sections in Alberta, British Columbia, and the Yukon Territory (Hansen, 1949; 1949a; 1950; 1952; 1953). This regional systematic and consistent pattern suggests the influence of white man and/or the dryer and warmer climate of the past 200 years (Lawrence, 1950). The evidence that lodgepole pine rather than spruce, was the predominant postglacial arboreal invader, emphasizes its great ecologic amplitude and its maneuverability under the physiographic instability in the wake of the retreating ice. As stated above, this is well substantiated by its postglacial record in the postglacial sedimentary columns of the Pacific Northwest, western Canada, and Alaska.

Fir (*Abies*) is represented at practically every level in all sections, and in general, becomes more strongly recorded northward in the transect of sedimentary columns (figs. 2-8). It is difficult to discern any definite successional trends in the fir pollen profiles in relation to other species or the environmental conditions. In the interior in the Fraser River Valley, fir pollen probably came from the higher slopes where alpine fir occurs rather sparsely. In the southern sector fir is best represented in the section 40 miles south of Merritt (fig. 2-B), where it occurs fairly abundantly on the upper slopes of surrounding mountains. The strongest record of fir is revealed in the sections along the Hart Highway north of Prince George, with the best representation at the site 116 miles north (fig. 7-C). This muskeg is in a montane region in

which the adjacent forests are composed of a high percentage of fir. Fir decreases northeastward from this site, and in the four muskegs nearest to Dawson Creek, is recorded to a maximum of only 8 percent (fig. 8-A). In general the record of fir in this study is similar to that in southwestern Yukon, northeastern British Columbia, and north central Alberta, while in west central Alberta it is most strongly represented in the lower levels indicating its existence farther down on the eastern slope of the Rocky Mountains during the cool, moist climate in the early Postglacial (Hansen, 1949; 1949a; 1950; 1952; 1953). It apparently has never played an important role in postglacial forest succession. The pollen record in southeastern Alaska suggests that silver fir (*A. amabilis*) has not migrated northward along the coast to any great extent during the Postglacial (Heusser, 1952).

Both western and mountain hemlock are represented in most of the sections, although the latter so sparsely and sporadically that no profile is shown. Western hemlock occurs sparingly in the Merritt section, but not in the other sections south of Williams Lake (fig. 2-B). It becomes more strongly represented in sections north of Quesnel and northwest of Prince George where it was frequently noted in the forest (figs. 4, 5). An occasional pollen grain of hemlock was noted in sedimentary columns north of Prince George, but on the east slope of the Rockies it apparently is entirely absent.

POSTGLACIAL CLIMATE AND CHRONOLOGY

The sites of all sections lie within the region of Cordilleran glaciation, probably Late Wisconsin (Mankato) in age (Antevs, 1945; Flint, 1947). The arboreal pollen record in most sections begins in the lowest organic sediments and even in the underlying silty deposits suggesting an early invasion of forests after deglaciation. There seems to be no distributional pattern with respect to the relative depths of sedimentary columns. The deeper sections occur in the dryer interior as well as in the moister areas, while the northern deposits are as deep as those in the southern sector. This suggests that the rate of accumulation of the organic sediments has been a response to local conditions rather than regional environments caused by climate and latitude.

The interpretation of the chronology of the recorded forest succession and climate can be only general as it must be based upon correlation with pollen studies elsewhere, position of the volcanic ash layers, the date of the thermal maximum as interpreted in other regions from pollen studies, varved clays, and radiocarbon dates that bear either a direct or indirect relationship to organic deposits and glacial-derived strata. The radiocarbon date of 11,400 years for the pre-Mankato Two Creeks Forest Bed has become an important starting point for the postglacial chronology of trends and events that are recorded by artifacts and sediments (Arnold and Libby, 1950). The figure of 11,000 years is set for the maximum advance of the Mankato stage because the ice actually moved about 25 miles beyond the forest bed in that region. This date and others derived by radiocarbon assay in eastern North America has suggested a round figure of 10,000 years for dating pollen records of peat sections lying on Late Wisconsin drift in eastern North America (Flint and Deevey, 1951). This does not mean, however, that the same date necessarily

applies to postglacial peat sections in the Pacific Northwest or western Canada, because much of the former lies south of the glacier terminus, and the fact that the glaciers originated from different centers.

In the Pacific Northwest the radiocarbon date of about 6500 years for the eruption of Mount Mazama, which resulted in the formation of Crater Lake, serves as chronological starting point (Flint and Deevey, 1951). The pollen record of postglacial vegetation in the northern Great Basin of south central Oregon reveals that grasses, chenopods, and composites attained their maximum near the time of the deposition of Mount Mazama pumice (Hansen, 1947). Farther north in eastern Washington, the pollen record of these same groups in 7 peat sections, also strongly portrays a thermal maximum, which is chronologically correlated in the region by the occurrence of a single volcanic ash stratum which has been assigned to Glacier Peak in north central Washington. The ash layer occurs at the level which these groups of plants attain their maximum. Quite some time before the radiocarbon dating method had been devised (Libby and Arnold, 1950), the author estimated the Washington ash at about 6000 years, on the basis that the warm, dry interval had been dated at between 8000 and 4000 years ago (Antevs, 1946; Hansen, 1947). The author also dated the eruption of Mount Mazama at about 10,000 years, as a compromise with his co-workers, although he believed that the pollen records in the northern Great Basin denoted a somewhat lower figure (Hansen, 1947). It would seem that the figure of 6000 years for the Washington ash is not too far off, in relation to the Mt. Mazama date, as both ash and pumice occur at a stratigraphic position at or near the grass-chenopod-composite maximum. If we assume there was no appreciable time lag in the development of the thermal maximum between south central Oregon and eastern Washington, these two periods of volcanic activity may not have been far apart in time.

The stratigraphic position of the Glacier Peak ash in the sections of this study seems to be about the same in relation to the recorded thermal stage as in Washington, although the expansion of grasses, chenopods, and composites is not so strongly marked. This would suggest that in more northern latitudes the xerothermic stage was not so well defined. This is further supported by the recorded increase in ponderosa pine at the expense of the more xeric plants in the upper levels of the Washington sections, reflecting a response of pine to a cooler and moister climate. In British Columbia, however, ponderosa pine has been an indicator of warmer and dryer climate and was replaced in the upper levels by species favored by cooler and moister conditions. Even beyond the present range of ponderosa pine the thermal maximum is slightly reflected although apparently the climate never warmed sufficiently to foster an influx of chenopods and composites (figs. 3, 4).

In southeastern Alaska, Heusser (1953) has interpreted a warm, dry period from pollen profiles as having been in effect between 5000 and 2000 years ago, as based upon a radiocarbon date. No such warming and drying seems to be recorded in the pollen profiles of coastal bogs in Washington and Oregon, however, while it is only slightly indicated in the Puget Lowland (Hansen, 1943; 1944; 1947).

The author has dated the Pacific Northwest sedimentary columns at between 15,000 and 18,000 years, as based upon the thickness and types of peat above and below the volcanic ash level of 6000 years (Hansen, 1947). In this study, what is assumed to be the same ash occurs at about the middle of those sections in which it is present. If the estimated age of 6000 years for the ash is used, it would suggest a total age of 10,000-12,000 years for the sections, assuming that the rate of peat deposition is constant. The rate of deposition of limnic peat, however, which lies below the ash horizon, is slower than that of fibrous peat, above the ash, so that greater age may be possible. These figures imply a somewhat greater age for peat sections in western than in eastern North America. This is not untenable, however, because the Cordilleran ice had a different center of origin than the eastern ice sheets and its proximity to the marine climate of the Pacific coast may have resulted in earlier withdrawal of the ice from this region.

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A LABORATORY STUDY OF VARVED CLAY FROM STEEP ROCK LAKE, ONTARIO

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ABSTRACT. Results of a laboratory study of some of the physical properties of varved clay from Steep Rock Lake are presented. Tests show a considerable variation in properties, especially water content and plasticity, between the light and dark laminae of varved clay. Grain-size analyses indicate that the Steep Rock varved clay are not diatactic. The test results suggest that flocculation resulting from varying physical-chemical conditions in the lake was responsible for the deposition of the varved clay.

INTRODUCTION

Throughout Canada, but especially in the northern areas, deposits of fine-grained glacial soils are found. These soils have frequently been the cause of a good deal of trouble to the construction and mining industries. When found in a saturated condition these soils often have the ability to liquefy whenever they are disturbed. The Division of Building Research of the National Research Council has undertaken a study of such northern soils. When high-grade iron ore was discovered beneath the waters of Steep Rock Lake and mining operations led to the dewatering of the lake and subsequent dredging of the lake bottom deposits, a good opportunity for study arose. The deposits of soil in Steep Rock Lake were for the most part varved clays, one of the more treacherous of the glacial soils. With the co-operation of Steep Rock Iron Mines Company Limited, the Division of Building Research undertook a detailed study of the Steep Rock varved clays with emphasis on the engineering standpoint.

At the outset of the study, varved clays were treated by the usual practice of soil mechanics, as a uniform soil. Testing was conducted irrespective of the laminations which make up the varved clay. The results of this study have been presented previously (Legget and Bartley, 1953). It was soon recognized that the separate laminations which make up a varve had remarkably different physical properties. Part of the detailed study was therefore directed toward finding the properties of the individual laminae and the variations in properties within the laminae.

This paper deals with some results of this detailed study. Although not the objective of the study, a good deal of information has been assembled which may be valuable to geologists. This paper presents the geological aspects of this study. The test results are discussed in the light of current theories concerning the formation of varved clays.

LABORATORY WORK

To carry out this laboratory investigation, block samples of a size which could be conveniently handled were collected by the author at Steep Rock Lake, sealed in paraffin or petrowax, packed in damp sawdust, and shipped to Ottawa for testing. Samples were taken from fresh exposures in order to preserve the natural water content of the varved clays. The samples were chosen from widely separated locations in the middle arm of Steep Rock Lake with the object of representing typical specimens of the varved clay which occurs in the Lake bottom. Once in the laboratory the samples were

split into fractions of light (summer) and dark (winter) layers for the various physical tests.

Natural water content.—The natural water content is determined by comparing the wet and oven-dry weights of the material. Oven drying was carried out at a temperature of 105°C. Since these soils were saturated, the amount of water present represents the volume of voids of the clay. The void ratio[1] was determined separately, by carefully trimming a sample, then weighing and measuring. In all cases it was found that the varved clays were at least 99 percent saturated. Since the water content also represents the void ratio of the clays, it is a measure of the structure of the soil. Water content tests were conducted with the objective of determining the variations in structure between the dark and light layers, and also the variations within any one layer.

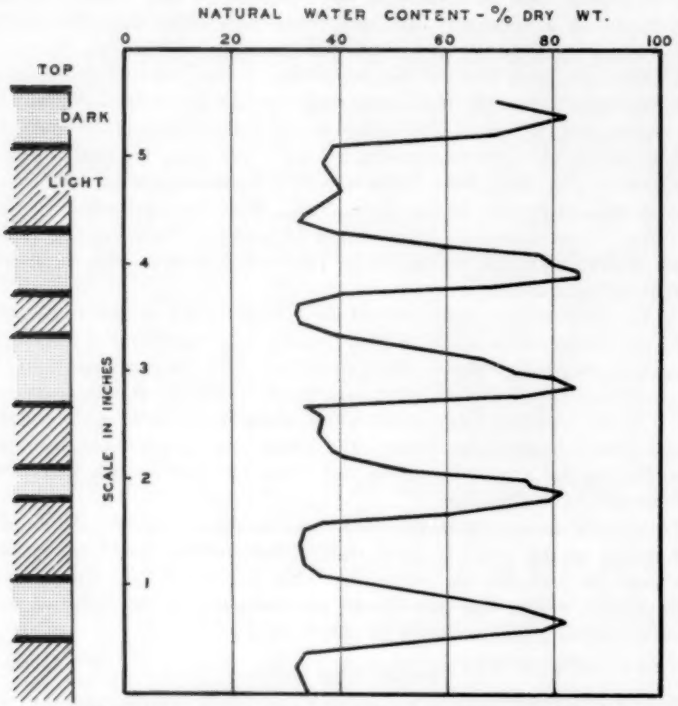


Fig. 1. Variation in natural water content within the varves (Sample 2-65).

The results of the water content determinations revealed a remarkable difference between the dark and light layers which make up a varve. Figure 1, which illustrates the variation found in one sample, is typical of the moisture content variations found in all the test work. The water content of the dark layers ranged from 60 to 100 percent, and of the light layers from 20 to 40

[1] Void ratio is defined as the ratio of volume of voids to the volume of the soil solids.

percent. This range in water content corresponds to a range from 1.69 to 2.83 in void ratio for the dark layers, and from 0.56 to 1.11 for the light layers. Thus the dark layers have a void ratio approximately 2½ to 3 times that of the light layers. The specific gravity of the soil particles was 2.80 and 2.76 for the dark and light materials respectively.

Plasticity.—The plasticity in clays is due to the molecular forces acting between small particles. These forces vary according to the structure of the clay particles, i.e. the type of clay mineral present, the size and surface development of the particles, and according to the concentration and type of electrolyte in the water. A kaolinite clay and a montmorillonite clay having the same grain size would have entirely different plasticity characteristics. In a system of pure kaolinite clay and pure water, Hauser and Le Beau (1946) attribute plasticity to molecular attraction forces between uncharged particles (van der Waals forces). Recent investigations show that plasticity is greatly influenced by the cation complex of the clay. Ahlberg (1951) found that the same clay treated with hydrogen, sodium, and other cations underwent great changes in plasticity depending on the cation.

The plasticity of the varved clays from Steep Rock was investigated by means of the Atterberg limits tests. This method has been standard in soil mechanics practice; a detailed procedure for the test may be found in A.S.T.M. "Procedures for Testing Soils" (1950) or in many of the reference books on soil mechanics. The Atterberg limits are made up of the liquid limit and plastic limit. The liquid limit is defined as the water content required to render the soil just fluid as distinct from plastic. The plastic limit is defined as the water content required to render the soil plastic as distinct from friable or crumbly. The difference in water contents between the liquid and plastic limits is the range in which the soil is plastic, and has been defined as the plasticity index. Highly plastic soils have a high numerical value for the plasticity index and conversely non-plastic soils have a value of zero for the plasticity index.

It should be noted that the procedure followed for determination of the liquid limit varied slightly from the standard procedure listed in A.S.T.M. (1950) whereas it is usual to conduct the liquid limit on soil which has been air dried, the values of liquid limit listed were determined on soil in its natural state. It was found that liquid limit determinations conducted on Steep Rock varved clays in their natural state yielded generally higher results than determinations conducted on air-dried samples.

The Atterberg tests revealed a great difference in plasticity between the dark and light layers. The change in plasticity is of the same order as that for natural water content and void ratio. Figure 2 shows the difference when the plasticity index is plotted against clay fraction (Skempton, 1953). Figure 3 shows the difference between light and dark layers when plotted on the Casagrande chart of plasticity index vs. liquid limit (Casagrande, 1947). In figure 4 the variations in plasticity within one varve are shown. This figure shows results which are typical of the variations found in other samples in which the layers are of more equal thickness. Figure 4 demonstrates a very rapid change in plasticity from dark to light material, as was the case with

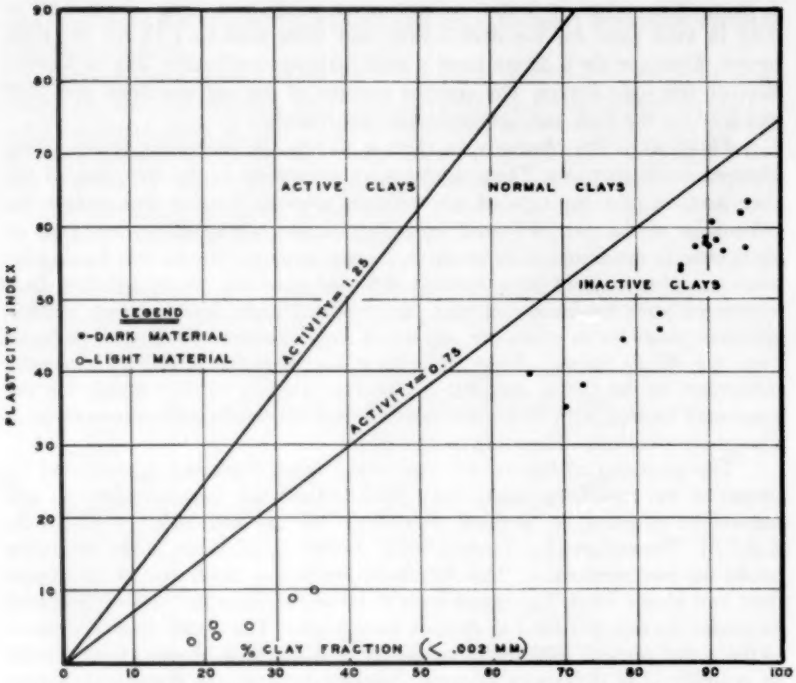


Fig. 2. Relationship between clay fraction and plasticity index (after Skempton).

water content and grain size. Figures 2 and 3 contain results of tests from all portions of the varves, and indicate no transitional zone of any appreciable thickness between the dark and light layers.

Grain size.—The investigation of grain size was directed toward determining the difference between the dark and light layers and whether any gradation in grain size existed within the varves. The techniques used for grain-size determinations were hydrometer analysis, pipette analysis, and measurement of individual grains under the microscope. The procedures used have been thoroughly investigated by various authorities. In the hydrometer analysis, the procedure followed was developed by Arthur Casagrande (1931) and is described by Lambe (1951). In the pipette analysis, the procedure outlined by Krumbein and Pettijohn (1938) was followed. Microscopic grain-size analysis was conducted by the technique given by Krumbein and Pettijohn (1938). The three techniques for grain-size analysis were found necessary because of the difficulty in obtaining a sufficient amount of soil to make any one test standard. Comparative tests were conducted on the same sample by both the hydrometer and pipette methods; the results were found to compare closely. It is difficult to conduct a comparison between the hydrometer or pipette methods with the microscopic method because, with the latter, the grain-size frequency is based on number rather than on weight as with the

other methods. The hydrometer and pipette analyses were conducted on samples which had been dispersed with a small amount of sodium oxalate.

The results of mechanical analysis for grain size are usually presented graphically by means of a grain-size distribution frequency curve or a grain-size distribution accumulation curve. Because of the large number of tests conducted, it is difficult to compare all the curves on one diagram. The values

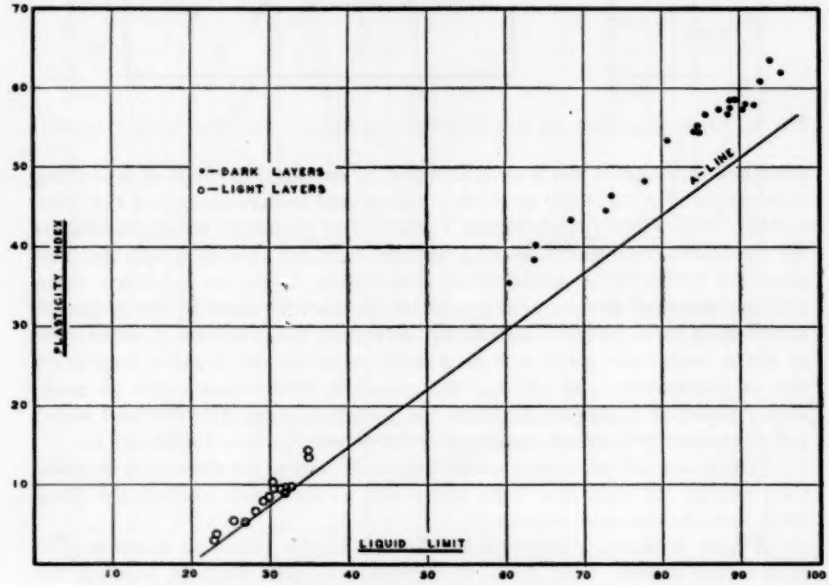


Fig. 3. Casagrande plasticity chart for Steep Rock varved clays.

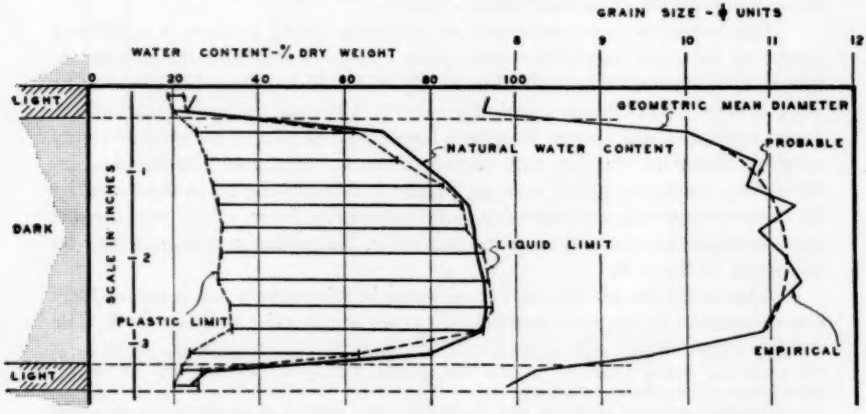


Fig. 4. Variations of grain size, water content, and plasticity within a varve (Sample 2-123).

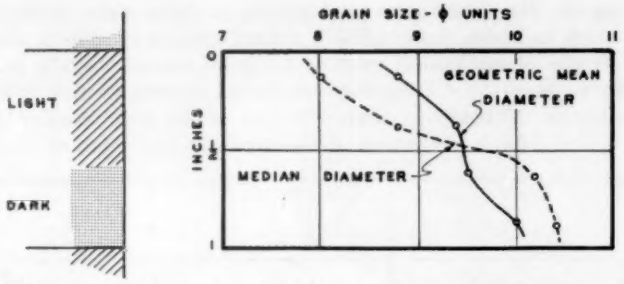


Fig. 5. Variation in grain size in a diatactic varve (Sample 38-3; Don Valley, Toronto).

presented in figures 4 and 5 were obtained by statistical methods of describing such curves. The statistical methods are described by Krumbein and Pettijohn (1938), Otto (1939), and Inman (1952). The geometric mean diameter is the size which corresponds to the grain-size diameter associated with the most abundant grains in an asymmetrical distribution. Using the geometric mean and the standard deviation it is possible to describe most of the grain-size distribution curve by two numbers. By converting the grain size in millimeters to the ϕ scale (the grain size in ϕ units equalling the negative $\log_2$ grain size in millimeters) and plotting the grain-size distribution curve on probability paper, it is possible to derive the geometric mean diameter and standard deviation by a simple graphical construction (Inman, 1952).

The grain-size tests were conducted to determine the difference in grain size between the dark and light layers and to determine whether the Steep Rock varved clays were diatactic.[2]

Figure 2 shows a significant difference in the clay-sized fraction. The dark layers contain from 65 to 95 percent clay-sized particles whereas the light layers contain only from 18 to 35 percent clay-sized particles. Figure 4 shows a significant difference within a varve.

The results of tests conducted on sublayers failed to show a significant gradation in grain size within one varve. Figure 4 indicates the results obtained from varved clay with abnormally thick dark layers (believed to be what Antevs (1951) terms a drainage varve). Although this varve is admittedly not typical, it was chosen because a large number of tests were made on it; tests conducted on samples with varves of normal thickness also failed to indicate any gradation within a varve. Figure 6 indicates the results obtained by the microscopic examination of a light (summer) layer which was divided into six equal fractions throughout its profile. No gradation was indicated by the results in figure 6.

Admittedly the number of varves tested in this manner are comparatively few in relation to the total number of varves which exist at Steep Rock. The

[2] Fraser (1929) defines diatactic structure of a varve as one in which the materials of the varve are sorted according to size and specific gravity of particles, the coarsest at the bottom and the finest at the top.

Symminct structure refers to clay deposited under control of an electrolyte, in which case particles large and small go down together and form an unsorted mass due to flocculation of the grains.

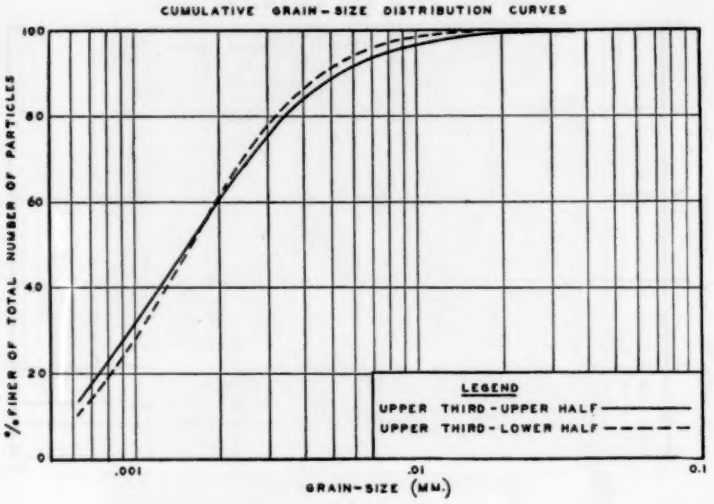


Fig. 6A

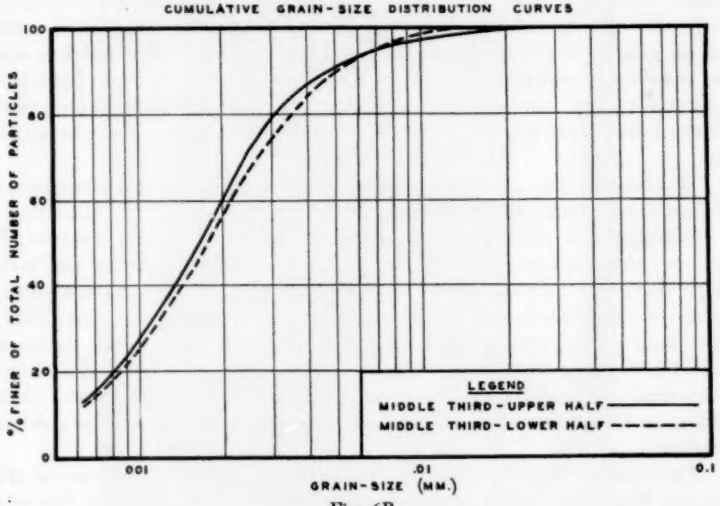


Fig. 6B

Fig. 6. A. Upper third—results of microscopic grain-size analysis of light layer of varved clay (Sample 2-124).

B. Middle third—results of microscopic grain-size analysis of light layer of varved clay (Sample 2-124).

C. Lower third—results of microscopic grain-size analysis of light layer of varved clay (Sample 2-124). (*See following page for fig.* 6C)

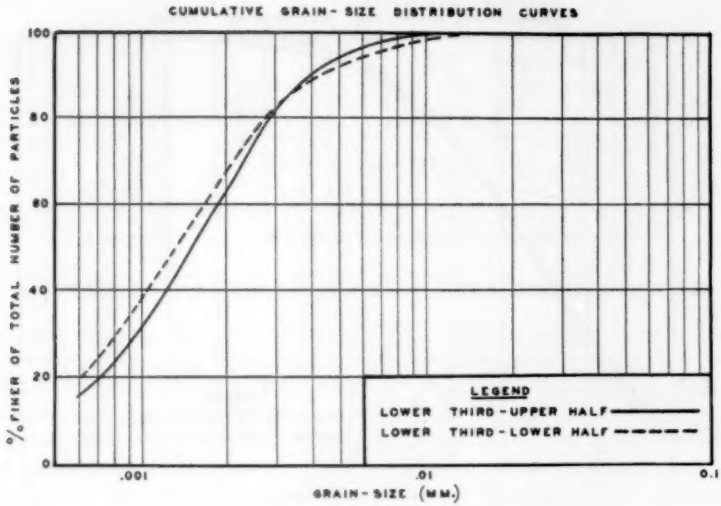


Fig. 6C

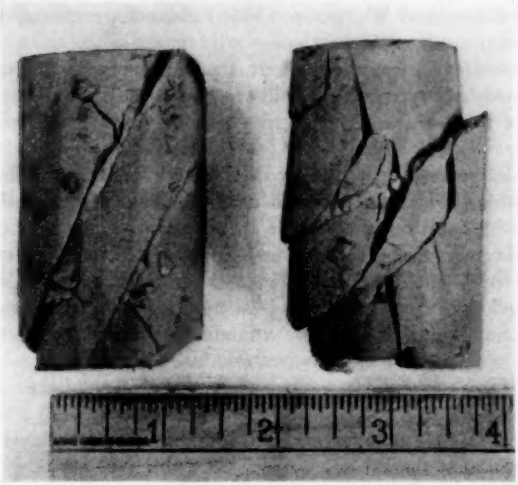
samples were, however, chosen to be typical of the various types of varves which were uncovered. In all the tests conducted on the Steep Rock varved clay, no gradation of particle size within a varve was indicated which is somewhat puzzling considering the work of Antevs (1951) on the Steep Rock clays. In discussing the formation of the Steep Rock varved clays, Antevs states that the laminations were diatactic, not symminct, and little flocculation took place.

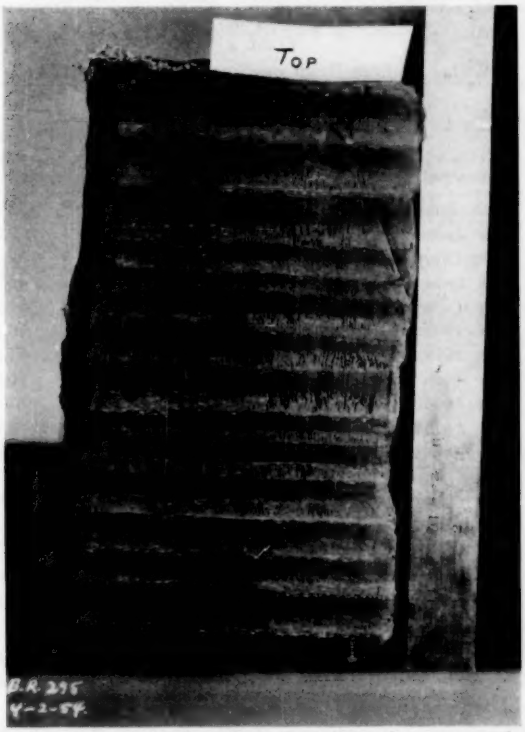
To compare this result with varves from other locations, samples were obtained from Amos, Quebec (through the courtesy of Dr. A. MacLaren of the Geological Survey of Canada) and from the Don Valley at Toronto. The Amos samples appeared very similar to the Steep Rock samples and lacked any particle-size gradation. The Toronto sample did appear to have a particle-size distribution; the results presented in figure 5 support this view. This is, in the author's opinion, a diatactic varve, while the Steep Rock varves are not. With the sample from Toronto, it could be seen that the light material grades gradually into the dark with no clear boundary line. In Plate 1, A and B, showing varves from Steep Rock, each side of the light layer has a definite boundary.

Rittenhouse (1934) conducted grain-size determinations on varved clays from the Wabigoon Valley about 80 miles from Steep Rock Lake. The grain sizes of varved clays from Wabigoon compare closely with those of Steep Rock (Legget and Bartley, 1953, fig. 13).

Thixotropy.—Thixotropy is defined as a reversible gel-sol-gel transformation in certain materials brought about by a mechanical disturbance followed by a period of rest. The word means "change by touch" and hence, since soil particles are solid materials, thixotropy applied to soils involves soil structure.

PLATE 1





A. Two samples of varved clay from Steep Rock Lake. Specimen on the left, $\theta = 30°$, failed along the light layer. Specimen on the right, $\theta = 60°$, failed through both dark and light layers. (Scale in inches.)

B. Typical sample of varved clay from Steep Rock Lake (Scale on right in inches).

According to Green and Weltmann (1946) thixotropy cannot exist without flocculation but the converse is not necessarily true.

The term thixotropy, as used in this paper, includes the state of "false body" as defined by Pryce-Jones (1948) as the two terms are so closely allied, and thixotropy has been used by many writers to cover both true thixotropy and false body.

Tests to determine the degree of thixotropy of soils are difficult to relate to field conditions. The laboratory investigation was directed toward merely proving the existence of a thixotropic state. The procedure followed was according to Ackermann (1948) and yields a result expressed in terms of water content called the "stiffening limit." This method is as follows. A small amount of soil is mixed with distilled water in a test tube. Sufficient water is added in small increments and thoroughly mixed until the point is reached when the soil paste will begin to flow when the test tube is inverted after a one-minute rest. The water content corresponding to this condition is termed the stiffening limit.

Again, a striking difference between the light and dark layers is revealed in their stiffening limits. Table 1 gives values obtained for sample 2-123 and may be compared with figure 4.

TABLE 1

Water Content Relationships for Sample 2-123
(in % oven-dry weight)

Sample no.	Type of material	Natural water content	Liquid limit	Plastic limit	Plasticity index	Stiffening limit
2-123-4	light (summer)	25.1	23.1	19.3	3.8	—
2-123-2	light (summer)	23.6	23.0	20.0	3.0	44.1
2-123-3	dark (winter)	69.5	63.8	25.5	38.3	165.8
2-123-4	dark (winter)	77.8	73.7	27.5	46.2	215.0
2-123-5	dark (winter)	84.6	84.1	29.3	54.8	211.0
2-123-6	dark (winter)	89.3	88.9	30.6	58.3	218.3
2-123-7	dark (winter)	90.2	88.8	31.4	57.4	201.0
2-123-8	dark (winter)	91.2	92.4	31.6	60.8	193.2
2-123-9	dark (winter)	92.8	93.7	30.2	63.5	198.8
2-123-10	dark (winter)	93.8	95.2	33.4	61.8	214.2
2-123-11	dark (winter)	92.5	91.9	34.0	57.9	209.4
2-123-12	dark (winter)	79.3	64.0	23.9	40.1	—
2-123-13	light (summer)	27.9	26.9	21.7	5.2	48.3
2-123-14	light (summer)	23.5	25.5	20.1	5.4	49.1

Other test results showed the same difference between dark and light layers. A few samples of the Steep Rock varved clay were tested by Boswell (1951) using a slightly different test. He reports values of 65 for the light layers and 120 for the dark layers. All the thixotropic tests show that both the light and dark layers of the varved clay are thixotropic, and hence must be in a flocculated condition.

Mineral analysis.—The mineral components of the varved clays were determined qualitatively by the techniques of differential thermal analysis

and X-ray diffraction. This work was done by the Crystal Chemistry Section of the Department of Mines and Technical Surveys, Ottawa, and revealed the following components for the light layers: quartz, carbonates, feldspar, clay (small amount), organic matter (trace); dark layers: quartz, feldspar, clay, probably montmorillonite, more than light layers, organic matter (small amount, slightly more than light layers).

The above analysis is borne out by the "Activity Chart," figure 2. Both the light and dark layers plot as "inactive clays," with the dark material displaying more activity than the light. This can be attributed to the relatively greater quantity of clay in the dark layers. Normally montmorillonite clay is considered to be an "active clay," but it plots as an "inactive clay" because of the masking effect of the quartz and feldspar mixed with the clay.

The mineral analysis reveals two important differences in the mineral characteristics of the dark and light layers. One is the relative amounts of true clay minerals, and the second is the fact that the light layers contain carbonates but that the dark layers do not.

Shear strength.—A few tests were conducted to determine the effect that the varved structure had on shear strength. The techniques used were the unconfined compression test and the direct shear test. Procedures for both these tests are well established and are described in detail by Lambe (1951).

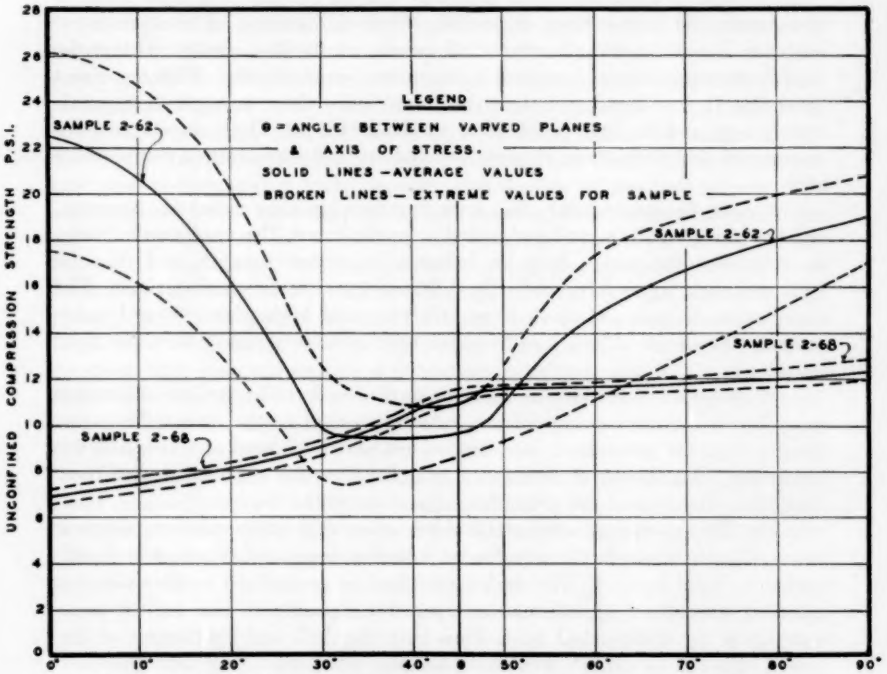

LEGEND
θ = ANGLE BETWEEN VARVED PLANES & AXIS OF STRESS.
SOLID LINES — AVERAGE VALUES
BROKEN LINES — EXTREME VALUES FOR SAMPLE
SAMPLE 2-62
SAMPLE 2-62
SAMPLE 2-68
SAMPLE 2-68
UNCONFINED COMPRESSION STRENGTH P.S.I.
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28
0° 10° 20° 30° 40° θ 50° 60° 70° 80° 90°

Fig. 7. Variation of unconfined compression strength with orientation of varves.

For the unconfined compression test, cylinders of undisturbed soil were trimmed, with due regard to the orientation of the varves, to a diameter of 1½ inches and length of 3 inches. This cylinder was subjected to axial compression, with the stress at failure being termed the unconfined compression strength. The Mohr theory of rupture shows that the shear strength is equal to one-half the unconfined compression strength for most clays. The test results for two samples are presented in figure 7 by showing the variation in unconfined compression strength with orientation of the varves. The difference between the two curves can be explained by the relative amounts of dark and light material in the samples. The dark layers were approximately twice the thickness of the light layers in sample 2-62, whereas in sample 2-68 the reverse was the case.

When $\theta = 30°$, failure took place entirely in the light layers as indicated in plate 1-A. Thus the value of unconfined compression strength at 30° represents nearly twice the shear strength of the light layers. The dark layers resisted deformation to a greater extent than the light layers. Because of this difference in stiffness, the departure of the curves for the two samples at $\theta = 0°$ is actually the strength of the light material, and because the effective area resisting load is less than indicated by figure 7, the strength is slightly lower at $\theta = 30°$.

Strength determinations on separate samples of dark and light material were conducted in the direct shear box. While this method of strength determination is not considered reliable for cohesive soils, it is considered that the relative strengths of the dark and light material are indicated. With the direct shear test, it was found that the dark layers had a shear strength of approximately 6 psi and the light layers of approximately 3 psi. These results compare reasonably well with shear strength derived from the unconfined compression tests.

It must be pointed out, that only two samples were tested for strength, and the above results must be regarded as preliminary. The results do indicate, however, that the varves have an influence on shear strength, and that the light and dark layers have radically different stress-strain characteristics. The dark layers, in spite of their loose structure and high plasticity and water content, appear to be much stiffer and have greater strength than the light layers.

Sensitivity.—Sensitivity is the term applied to describe the loss of strength in a clay when it is changed from the undisturbed to the remoulded state. Results from the unconfined compression test have been used as a criterion for sensitivity. The degree of sensitivity is defined as the ratio of undisturbed strength to the remoulded strength, at the same water content.

The light material, when remoulded at natural water content, did not have sufficient strength for a cylinder 3 inches long and 1½ inches in diameter to stand by itself. The dark layers had an unconfined compression remoulded strength of approximately 1 psi or one-twelfth of that for the same material in the undisturbed state. Thus both the dark and light layers of the varved clay can be classified as extra-sensitive soils (Skempton and Northey, 1952).

DISCUSSION OF TEST RESULTS WITH REGARD TO THEORIES ON VARVING

Before discussing the test results, it is necessary to review some of the theories on the formation of varved clays. The word "varved" implies a distinctly banded deposit. Thus a varve is usually defined in geological literature as material which can be definitely identified to have been deposited in one year, and is quite distinct from preceding or succeeding years. Baron Gerard de Geer, a Swedish geologist, first recognized the significance of these laminations and suggested the annual theory of deposition. Each varve consists of a couplet, a light-colored relatively coarse summer layer, and a darker-colored fine-grained winter fraction. Varved clays are usually associated with glacial lakes, and were formed during a time of retreat of a glacier. De Geer believed that during the summer when large volumes of melt water charged with glacial debris reached a lake or settling basin, the relatively large particles would settle out. In the winter, when the lake was covered with ice, and no further fresh material was supplied, the fine-grained material carried in suspension was given sufficient time to precipitate. Thus a varved couplet was formed each year.

Antevs (1951) has conducted a detailed study of the varved clays at Steep Rock and has written an account of the types of varves found and discussed their mode of formation. He discovered eight separate series of varved clays corresponding to eight different conditions of environment. As previously mentioned, Antevs believes the Steep Rock varves to be diatactic and lists seven conditions which affected the deposition of the Steep Rock clays. These seven conditions are as follows: (1) restriction of appreciable mud supply to the summer months; (2) fluctuation of mud influx and of the currents; (3) differential rate of settling of unequal grains and particles; (4) low temperature and accompanying high viscosity and density of the lake waters; (5) semistratification or isothermy of the lake water and oscillations between these states; (6) height of fall of the particles; and, (7) variations in the concentrations of the electrolytes. Antevs has covered the formation of the Steep Rock clays completely, and the results presented in this paper can only supplement particular aspects in Antevs' theory. Only on the point that the Steep Rock varves are diatactic, does the author disagree with Antevs. This is on the point that diatactic implies a gradation in particle size within the varve. Before developing the argument further, it is necessary to examine the condition necessary for the formation of diatactic varves as laid down by Fraser (1929).

Using a specially constructed tank in which the temperature of the water could be closely controlled, Fraser conducted experiments on the formation of varved clays, especially diatactic varves. From his experiments, Fraser concluded that the following conditions were necessary for the formation of varved clays:

(a) The lake was one of quiet waters and had a practical absence of erosion;
(b) The supply of material was not flocculated;
(c) The lake waters contained a very low concentration of electrolytes.

Fraser's experiments led him to conclude that diatactic varves were formed subject to the restrictions that follow:

(i) During the melting season there would be a continuous supply of material, unflocculated and of assorted sizes. The coarser materials would settle relatively rapidly. Because of the cold water, the fine material would settle very slowly. The settling velocity would be a direct function of the temperature of the water and particle size. Because of the difference in settling velocities between coarse and fine material, the sediment would have a definite grading, with coarser material at the bottom of the varve and becoming progressively finer as the varve was built up;

(ii) At the close of the melting season, the supply of fresh material would dwindle to practically zero. Thus nearly all the coarser material would be deposited during the summer, and the division between the light and dark material would correspond approximately to the close of the melting season;

(iii) During the winter season, with no fresh supply of material the fine material would be partially aided by flocculation. This flocculation would result from an increased salinity because of the increase in the concentration of electrolytes supplied over the melting season. Fraser's experiments showed that flocculation would be retarded by the cold water. In any case the salinity could not increase to a point greater than one-fiftieth of normal sea water to permit varving. Fraser thought that this small degree of salinity would not affect the coarser particles sufficiently to cause flocculation, because the larger the particle, the more indifferent it is to flocculation;

(iv) The periodic supply of material thus outlined would continue on an annual cycle.

Considering the laboratory tests described in this paper, the results of the grain-size tests revealed no gradation of particle size within the laminae. This suggests that the Steep Rock varves are not diatactic. The water content tests show the clays to have a very loose structure, and because both the light and dark material exhibit thixotropy, it is thought that both the light and dark material were flocculated. Legget and Bartley (1953) in describing the hydraulic dredging carried out at part of the mining operations, point out that the soils, when redeposited in the lake waters, remain in particle assemblages, with a mean diameter of about 0.01 millimeters. This indicates that the soil particles have strong forces acting between them to cause this flocculation. The mineral analysis revealed that the light layers contained carbonates, although the dark layers were void of carbonates. This point is worth noting in the light of Burwash (1938) and Arrhenius (1947).

Burwash (1938) suggests that the change in the capacity of the lake waters for holding dissolved carbon dioxide and hence its capacity for dissolving calcium carbonate may be responsible for the deposition of varved clays. In the winter, with a relatively large concentration of carbonic acid, the lake waters are well equipped to maintain calcium carbonate in solution. In the spring, as the lake waters become warm, the carbonic acid is given up, leading to precipitation of the carbonates. This, Burwash believes, leads to the formation of calcite concretions in the light or summer layers. As reported

by Legget and Bartley (1953), concretions at Steep Rock are found only in the light layers of the varves.

Arrhenius (1947) in attempting to explain the causes for the great difference in color between the dark and light layers, found that the dark or winter material showed dissolution by carbonic acid on a far greater scale than the summer material. Arrhenius reported on varved marls which occur in Sweden, but in the opinion of the author this fact supports Burwash's theory.

By chemical analysis of three varved clays from Northern Manitoba and Toronto, Wallace also showed the light layers to contain more carbonates than the dark (Wallace, 1927, p. 111).

The difference in plasticity between the dark and light material may be due to three causes. First, the dark layers contain more clay minerals, which would increase plasticity. Secondly, the light material is slightly coarser, thus has less surface area, which would reduce its plasticity. A third cause could be different cation complex in the clays, brought about by changes in the depositional environment. Test results bear out the first two points but there is no proof for the third.

In conclusion, the test results presented in this paper indicate that both the dark and light layers of the varved clay at Steep Rock were affected by flocculation in their deposition. Grain-size results show that they cannot be termed diatactic as defined by Fraser (1929). Regarding their mode of formation, the results lend support to the theory put forward by Burwash.

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REVIEWS

Causalités et accidents de la découverte scientifique; by R. TATON. P. 171; 7 figs., 32 pls. Paris, 1955 (Masson et Cie., 980 frs.)—As our scientific civilization becomes more and more complex and as science advances and intrudes itself more and more into the very fabric of everyone's daily life, the question of the methods and processes of scientific discovery becomes increasingly more important, not only to the historian, the social scientist and the student of the modern world, but to the educated layman as well. Just what does the scientist do? how does he think? how are great discoveries made? what are the factors which encourage or discourage scientific advance? Since the modern world has put its reliance in science as the most important means of achieving its ideals, these questions are basic ones if we are to understand the intellectual environment in which we live.

René Taton, one of France's finest young historians of science, has attempted to answer these questions in this book, and his attempt has been largely successful. Beginning with the psychology of invention, he shows quite clearly, by the use of excellent examples drawn from the physical and natural sciences, some of the ways in which scientists break through the orthodoxy of present theory and seize an idea which allows them to achieve a new synthesis and create a new theoretical structure. But he also shows that pure reason or intuition are in many cases not sufficient. The scientist is dependent upon the technological aspects of the period in which he lives which, because of the inability to create certain instruments, may prevent him from arriving at conclusions which can be checked by observation. He also is involved in the general intellectual attitude of his day, and this attitude, as with Galileo, may serve as a block to further progress or, as with Mendel, may merely be one of indifference which allows his work to fall on deaf ears. All these factors and more besides are illustrated with excellent examples drawn from the history of science, and the text is accompanied by well-chosen plates which underline Taton's points and make them perfectly clear to all.

The only major criticism that I would make of this work is that Taton devotes very little space to the social milieu in which science has thrived. Why did science achieve its present intellectual hegemony in the modern world? What has been the effect, for science, of this hegemony? How has the utilization of science by all the governments of the world affected the ways in which the scientist can do his work? These topics are touched upon, but they are certainly relevant to the problem of scientific discovery and advance and therefore deserve somewhat more space than they are here given.

What M. Taton has done, however, he has done well. The book is clearly written although marred by errors in printing. It is well indexed. It is a work which most scientists, historians and philosophers, as well as the interested layman, will want to add to their libraries. L. PEARCE WILLIAMS

Progress in Low Temperature Physics, Vol. I; edited by C. J. GORTER. P. xviii, 418; 177 figs. New York and Amsterdam, 1955 (Interscience Publishers Inc., and North Holland Publishing Co., $8.75).—This volume, edited by the distinguished director of the Kammerlingh Onnes Laboratory at Leiden, is a collection of eighteen review articles on phases of low tempera-

ture physics of particular current interest. The authors of individual chapters include many of the leaders of low temperature research and each writes on a subject to which he has made original contributions. The articles are thoroughly documented with references to the literature; the bibliography alone makes this book valuable as a reference work. On the whole, enough descriptive and historical background is given to make this book attractive for the specialist and non-specialist alike.

Low temperature physics is not really a field separate and distinct from other branches of physics. Instead low temperature physics problems cut across boundary lines and include aspects of nearly every division of physics. The intense interest in the region near the absolute zero of temperature in recent years is due in considerable measure to certain anomalous effects that occur only at these temperatures. The amazing superfluidity of liquid helium (with its creeping film frictionless flow, etc.) and the superconductivity of certain metals have had particular fascination to physicists and are treated in many aspects in this book. As an example, anyone curious as to what a "roton" is should enjoy the excellent qualitative discussions of R. P. Feynman in his chapter on the quantum mechanics of liquid helium. The rest of the book is devoted to low temperature aspects of magnetism and certain other problems.

No attempt has been made to cover low temperature physics completely in this one volume; indeed, that would be impossible. However, by labelling this book Volume I, Professor Gorter makes an implied promise to include other topics in a future volume. The quality of this first volume ensures a demand for more.

HENRY A. FAIRBANK

Inorganic Reactions and Structure; by EDWIN S. GOULD. P. viii, 470. New York, 1955 (Henry Holt and Company, $6.50).—There has been an increased demand in the last few years for a comprehensive and stimulating textbook of inorganic chemistry for senior undergraduate students majoring in chemistry. Existing textbooks on inorganic chemistry are mostly either too bulky or too elementary to be used as such a textbook. *Inorganic Reactions and Structure* seems to be a satisfactory answer to this demand.

The book starts with a qualitative description of atomic structure, the covalent bond, hydrogen and hydrides, oxygen and oxides, acids and bases, the alkaline and alkaline earth metals. Then, after a chapter on the periodic table, the individual groups of important elements are discussed one by one. The chapters are short, tersely written, and stimulating. Applications of physico-chemical principles and methods to specific examples in inorganic chemistry are presented throughout the book with minimum amount of mathematics. There are also very readable chapters on inorganic nomenclature, X-ray studies, metal chelates, magnetic, dielectric and spectral studies.

The exercises at the end of various chapters contain many interesting problems. Although references to the original literature have been omitted in this book, these can be easily supplied to the student by a competent instructor.

The last chapter on nuclear reactions seems to be the least satisfactory. While for the general reader this chapter contains little new material beyond what he had already learnt from a good general chemistry course, for the

really ambitious student it may be more efficient to turn directly to radiochemistry textbooks.

A very useful table of some numerical properties of the more familiar elements is given in Appendix II. JUI H. WANG

The Genetics of Paramecium aurelia; by G. H. BEALE. Cambridge Monographs in Experimental Biology 2. P. xi, 179; 11 figs. New York, 1954 (Cambridge University Press, $2.50).—This volume, second of the Cambridge Monographs in Experimental Biology, admirably fills the need for a general review of this highly significant phase of modern genetic research. It is a surprising fact that modern genetics is practically unknown in the protozoa outside of *Paramecium aurelia*. Surprising for two reasons: first, that the rich protozoological heritage of the 19th century has not received more attention from contemporary geneticists, and second, that the many intriguing morphogenetic and cytological features of this phylum have not attracted more of these biologists.

Beale's presentation of the genetics of *P. aurelia* affords a stimulating insight into the striking potentialities inherent in these studies for getting at certain problems of general biological interest. The subject is divided into six chapters: Introduction, The Material, The Killers, The Antigens, The Mating Types, and Conclusion. There is also an extensive bibliography. The treatment of each topic is very thorough. General introductory remarks are followed by careful discussions which are supported in many cases by the original data.

The few faults that this reviewer found with the book were minor. One example is the perpetuation of the error that conjugation, cytogamy, and autogamy are reproductive processes. They are purely sexual processes. Only by fission does one paramecium produce more paramecia. Another example is the omission, except for a single passing reference, of the problems of ageing and the role of nuclear reorganizations in rejuvenescence. It is realized that the latest and most revealing work on this topic has only recently been made public, too late for inclusion in this volume. Beyond this recent work, however, there is a great deal of information well worth inclusion in this monograph.

To those especially interested in genetics the book can be highly recommended. For biologists in general *The Genetics of Paramecium aurelia* can well serve as an excellent introduction to the results and potential of this field of biologic experimentation. EARL D. HANSON

An Introduction to Plant Taxonomy; by GEORGE H. M. LAWRENCE. P. viii, 179; 69 figs. New York, 1955 (Macmillan Company, $3.25).—The preface to this little volume indicates that it is written for "the adult amateur botanist and the student of a local flora course at the college level." Dr. Lawrence, well-known for his *Taxonomy of Vascular Plants* (1951), has drawn freely from his earlier work in preparing a book suitable as a text in a one-semester introductory taxonomy course. A review of contemporary and historic systems of classification, an extensive and detailed consideration of plant

structures important in taxonomy, and a brief survey of a few important plant families form the major portion of this book. A chapter on the biographical history of taxonomic studies in North America adds background and perspective.

The work, while introductory in nature, is far from elementary in approach. It is not likely to convert anyone with a casual interest in the naming of plants. The fifty-eight pages devoted to plant structures and terminology are rather forbidding to the uninitiated (e.g. five pages dealing with thirty-nine leaf vestiture types). Botanists familiar with *Gray's Lessons in Botany* (1887) will recognize the morphological and anatomical approach. Eight pages are devoted to the vascular cryptogams and Gymnosperms. The twenty-six pages of angiosperm families, arranged strictly in accordance with the outmoded Engler system, treat only paragraphically thirty-five families of dicots and seven families of monocots. It is the author's contention that three-fourths of the wild flowers and native trees of "most parts of the United States and Canada" are to be found in the families treated. No attempt is made to synthesize any phylogenetic relationships from the material presented.

The Glossary and Index are combined and quite extensive (32 pages) and together with the chapter on Plant Structures should guide the student or non-taxonomist through the keys of most manuals or floras in North America. The short chapter on Collecting and Identifying techniques will interest and satisfy the reader who wishes to catalog and preserve floral material. A lucid review of the salient features of the International Code is presented in the section on Nomenclature. The volume is well illustrated, although it is unfortunate that a uniform system of identifying the illustrations was not followed. Such typographical errors as appear in the text are of little note. Floral diagrams, which are frequently of use to beginning students as an aid in "keying out" a specimen, appear in one illustration but are nowhere defined or explained in the text.

With the possible exception that too great an emphasis has been placed on structure and terminology at the expense of a more integrated and comprehensive introduction to the plant families, this book should prove to be a useful text and supplement to the use of a manual in a local flora course. In addition, it should prove useful to the non-taxonomist who may have reference to plant material.

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